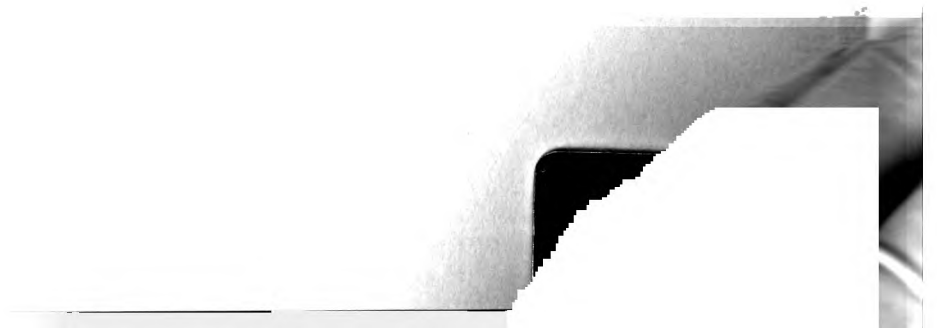
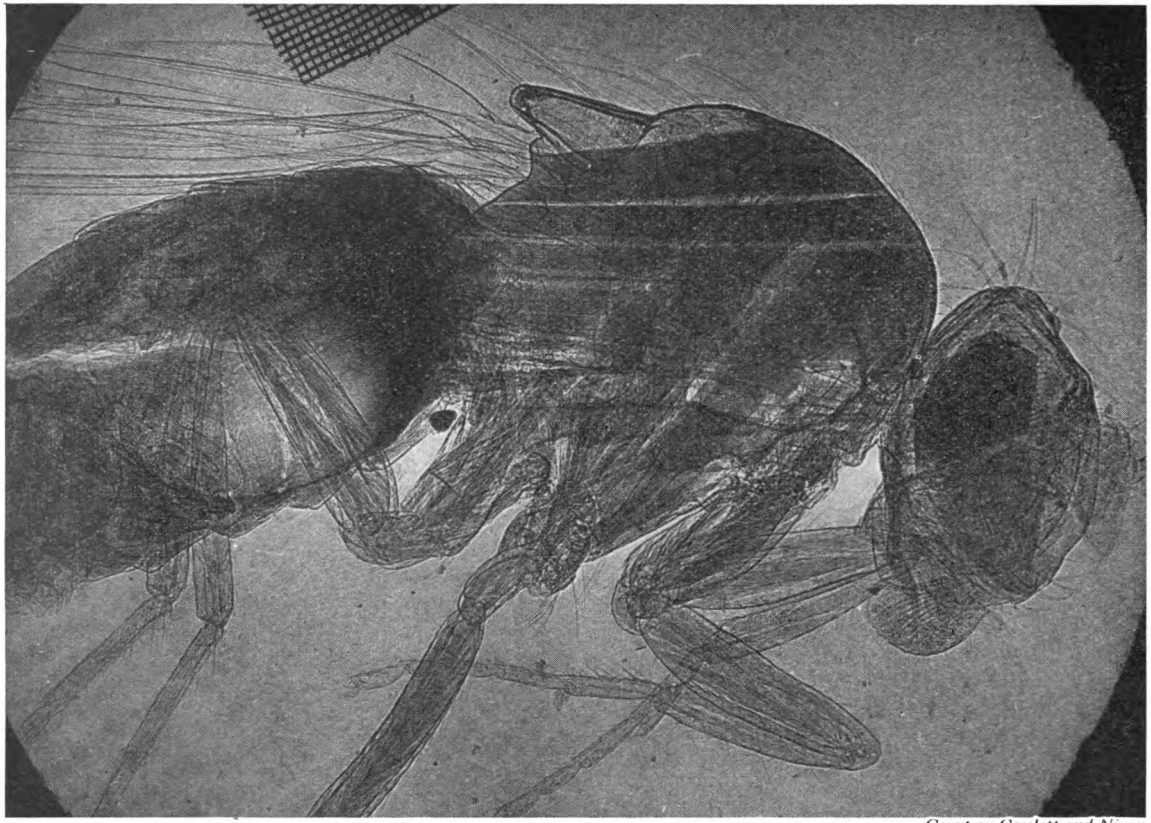
A 767,696

PROPERTY OF
University of Michigan Libraries
1817
ARTES SCIENTIA VERITAS



RADIOLOGY PHYSICS



Courtesy Cosslett and Nixon

Microradiograph of *Drosophila melanogaster* (fruit fly), freeze-dried. Primary magnification ×20; enlargement factor ×7·5; total magnification ×150. The pattern in the upper left corner is a portion of a silver grid, 1500 meshes per inch.

RADIOLOGY PHYSICS

AN INTRODUCTORY COURSE FOR RADIOLOGISTS, RADIOGRAPHERS AND MEDICAL STUDENTS

BY

JOHN KELLOCK ROBERTSON
M.A., LL.D., F.R.S.C., F.INST.P.
FORMERLY PROFESSOR OF PHYSICS, QUEEN'S UNIVERSITY
KINGSTON, CANADA

D. VAN NOSTRAND COMPANY, INC.
PRINCETON, NEW JERSEY
NEW YORK

Phoenix

QC
475
.R65
1956

PRINTED IN GREAT BRITAIN

37-111235

Y=4.S7:

TO

LORRAINE

'The details of knowledge which are important will be picked up *ad hoc* in each avocation of life, but the habit of the active utilization of well-understood principles is the final possession of wisdom.'

A. N. WHITEHEAD

PREFACE TO THE THIRD EDITION

In this edition much new material has been added and a fair amount considered either obsolete or unnecessary, dropped. The additional work includes a new chapter on Radiography and Microradiography, sections on the oscilloscope, the image intensifier, the scintillation counter, the rad and the rem, the different types of synchrotrons and the linear accelerator, and much new material on the physics necessary for the use of radioactive isotopes. An important Appendix on protection has been added. The revision has made possible also the introduction of many minor changes and the addition of certain topics such as inherent regulation, the meaning of cross-section, average life, secular and transient equilibrium, photoelectric timer, and tomography. It is hoped that this edition will be of enhanced value to students of both therapy and diagnosis.

The original character of the book has been maintained, its aim being to explain as simply as possible the basic physical principles necessary for the intelligent use of applications of physics in medicine and of radioactive isotopes. Although a knowledge of only elementary mathematics is necessary, wherever possible the work is treated quantitatively, with considerable emphasis on the solution of problems.

In the preparation of the book it is a pleasure for the author to acknowledge his indebtedness to many people and to a number of commercial firms. So many fellow physicists have given help, either directly or indirectly, that it is not possible to give a complete list, but special mention must be made of courtesies shown by Mr. W. J. Meredith, Chief Clinical Physicist of Christie Hospital and Holt Radium Institute, Manchester; Professor J. E. Roberts and Dr. H. F. Cook, of Middlesex Hospital, London; Professor J. Rotblat and Dr. J. W. Boag, of St. Bartholomew's Hospital, London; Professor G. Stead and Professor C. B. Allsopp, of Guy's Hospital Medical School; and Professor F. W. Spiers of the University of Leeds. Most of all, the author is grateful for acts of kindness too numerous to list to Professor W. V. Mayneord and his secretary, Miss Audrey Morrell, of the Royal Marsden Hospital, and to many members of his department, especially Dr. L. F. Lamerton, Dr. G. Spiegler, Dr. N. G. Trott, Miss G. M. Clark, Dr. E. H. Belcher and

Mr. H. J. D. Ireland. It is a pleasure also to thank Sir Edward Bullard and Mr. W. E. Perry of the N.P.L. for literature relating to the standardization of radioactive isotopes in Great Britain; to Mr. W. E. Schall for the gift of a diagram and for permission to use a diagram from an early edition of his book *X-rays, their Origin, Dosage and Practical Applications*; to Dr. S. W. Shellshear for the loan of notes; and to Mr. R. S. Wright for literature relating to stabilizers. The author is greatly indebted to Dr. V. E. Cosslett and Dr. W. C. Nixon both for the gift of the photograph appearing in the frontispiece and for reading, with helpful comments, the chapter on Radiography and Microradiography.

Much of the preparation was done in the library of the British Institute of Radiology, and the help given by Miss G. Davey, General Secretary, Miss M. Powell and Mr. A. E. Atkins is warmly appreciated. Grateful thanks are also due to K. C. Denley, of the Society of Radiographers, for the gift of literature.

Valuable help has been received from a number of commercial firms and their representatives. Special thanks are due to Miss K. C. Clark and Mr. W. Watson of the Ilford Department of Radiography and Medical Photography; to Isotope Developments Limited for the gift of a photograph of a scintillation counter head; to Kodak Limited for information about photographic emulsions; to Mr. R. H. Bull of Atomic Energy of Canada Limited for the gift of a photograph of the theratron; to the Controller of H.M. Stationery Office for permission to use two photographs of a Harwell reactor; and, for literature and help, to E.M.I. Research Laboratories Ltd., Marconi Instruments Ltd., and Watson and Sons (Electro-Medical), Ltd. Philips Electrical Ltd. have supplied the author with so much material, much of which has been used, that a word of special thanks is due to them.

Acknowledgement should also be made of the author's use of a *Glossary of Terms used in Radiology*, soon to be published by the British Standards Institution.

J. K. R.

HAMPSTEAD, LONDON
April, 1955

PREFACE TO THE SECOND EDITION

THE developments in nuclear physics which were announced to the world with dramatic suddenness in August 1945 are of great importance in the field of radiology and have made a second edition of *Radiology Physics* desirable. In carrying out the revision, the author has added new work in atomic physics and at the same time has taken the opportunity to overhaul the whole book, rearranging the order and amplifying where necessary. The elementary character of the book has been maintained, for it is essentially an introduction to a vast field whose importance in biology and in medicine is now fully recognized.

In the preparation of the manuscript the author has consulted freely current literature on nuclear and atomic physics and, in particular, would like to express his indebtedness to *Medical Physics*, edited by Otto Glasser, and to *Lectures in the Physics of Radiotherapy* by M. V. Mayneord, complimentary copies of which were received from the Ontario Institute of Radiotherapy. Acknowledgement is gladly made of helpful suggestions received in conversation with Professor Mayneord, of the Royal Cancer Hospital, London, and with my colleague, Dr. H. M. Cave. A number of new illustrations have been introduced and, for some of them or for permission to use them, my grateful thanks are due Dr. Matthew Luckiesh, Dr. Edith Quimby, Professor Pierre Demers, Professor Serge A. Korff, The Victoreen Instrument Company, Machlett Laboratories, Incorporated, *Radiology* and Dr. J. M. Cork.

The author would like to take this opportunity of expressing his appreciation of helpful comments made by many after the original publication of *Radiology Physics* and, in particular, to thank Dr. Marvin M. D. Williams, of the Mayo Foundation, Rochester, Minn.

J. K. R.

QUEEN'S UNIVERSITY
May 1948

PREFACE TO THE FIRST EDITION

WITH the ever increasing applications of physics in medicine the problem of giving the medical or the premedical student adequate instruction in physics has become one which demands action. To teach in one year the fundamental principles of physics, and at the same time to deal adequately with those applications with which a medical student should be familiar, is well nigh impossible. At Queen's University the problem has been solved and, on the whole, satisfactorily, by giving instruction in two successive years. In the first year, the student is given the usual course in general physics, with the omission of electricity and magnetism. In the second year, lectures and laboratory work in electricity and magnetism lead naturally to a consideration of such topics as X-ray transformers, X-ray tubes, conduction of electricity through gases, radioactivity, nuclear physics, and high frequency currents. *Radiology Physics* covers, with some amplification, the work given by the author in the second half of this course.

It is hoped that this book will prove suitable as a text for similar courses elsewhere, especially for those institutions which agree with the Committee on the Teaching of Physics for Premedical Students* in their opinion " that the American Association of Physics Teachers should go on record as in favour of making the physics prerequisite two years instead of one ". *Radiology Physics* is also commended to all radiologists and radiological technicians who wish, not a handbook, but a simple explanation of the physical principles underlying the use of their apparatus. Although a knowledge of elementary electricity and magnetism is assumed, the mathematical treatment is reduced to a minimum.

In the preparation of the manuscript, the author has made some use of an earlier book on *X-rays and X-ray Apparatus*, and his thanks are due the President of D. Van Nostrand Company, Inc., for permission to use some of the material in the more recent *Atomic Artillery*. Under each illustration due acknowledgment is made where necessary, but my special thanks are due the Philips' Gloeilampenfabrieken, Eindhoven, Holland, the General Electric X-ray Corporation, Dr. J. G. Trump of the Massachusetts Institute of

* *The American Physics Teacher*, 5, 267, 1937.

Technology, and Mrs. Edith Quimby and Dr. G. Failla of the Memorial Hospital, New York, for photographs and other material. Acknowledgment is also made of the kindness of Mr. A. C. Baldwin, Mr. G. E. Simons, and Dr. J. Gross, of the General Electric Corporation, and Mr. Victor Hicks of the Westinghouse X-Ray Company.

It is a pleasure to thank my wife for her valuable asistance throughout the preparation of the book, and my colleagues Dr. B. W. Sargent, who read part of the manuscript, and Dr. H. W. Harkness, who read the chapters on high voltage. With Dr. Sargent the author has had many discussions. My friend and colleague Dean A. L. Clark has again provided clerical and other assistance and it is a pleasant duty to express to him my appreciation.

J. K. R.

QUEEN'S UNIVERSITY
KINGSTON, CANADA
October, 1940

CONTENTS

CHAPTER PAGE

I. ALTERNATING CURRENTS 1

Electromagnetism — Electromagnetic Induction — Alternating Currents—Strength of a.c.—Meaning of r.m.s.—Inductive and Noninductive Circuits—Impedance and Inductive Reactance—Capacitive Reactance—Combination of Resistance and Capacitance—Resistance, Capacitance and Inductance in Series—Parallel Resonance—Phase Difference—Power Factor —Capacitance and Phase Difference—Problems and Questions.

II. PRODUCTION, MEASUREMENT AND CONTROL OF HIGH VOLTAGE. PART I 21

The Transformer—Insulation—Efficiency and Power Rating of Transformer—Inherent Regulation—Transformer Rating—Spark-gap Meter—Corona—Primary Voltmeter—Electrostatic Voltmeter—Current through a High Resistance—The Seeman Spectrograph—Control of Tube Voltage by Rheostat—Control of Tube Voltage by Auto-transformer—Static Stabilizer—Problems and Questions.

III. CATHODE RAYS 36

Conductivity of Air—Conductivity of Air at Reduced Pressure—Appearance of a Vacuum Tube—Properties of Cathode Rays—Nature of Cathode Rays—Structure of the Atom—Meaning of Ionization—Ionization by Collision—Electron Bombardment—Origin of Roentgen Rays—The Oscilloscope—Problems and Questions.

IV. POSITIVE RAYS AND ISOTOPES 53

Nature of Conductivity at Atmospheric Pressure—Conductivity at Reduced Pressure—Positive Rays—Chemical Analysis by Positive Rays—Isotopes—Determination of Atomic Weights by Physical Method—Discovery of Deuterium—The Proton—Separation of Isotopes—Heavy Water—Problems and Questions.

V. ROENTGEN TUBES 66

Two Types of Tubes—Thermionic Emission—Hot Filament Rectifiers—Hot Filament X-ray Tube—Focusing—Methods of Cooling a Target—Control of Tube Current—Voltage Stabilizer—X-ray Protection and Metalix Tube—Line Focus —Rotating Anode—Rating—Shockproof Tubes—Oil-Immersion—Low Voltage Tubes—Low Voltage Tube Emitting Rays of High Intensity—Problems and Questions.

CHAPTER PAGE

VI. RECTIFICATION, DIODE AND TRIODE VALVES 88

Self-rectifying Tubes—Valve Rectifiers—Types of Valves—Half-wave Rectification—Full-wave Rectification—Tube Rating and Type of Rectification—The Use of Condensers with Valves—The Greinacher Circuit—The Villard Circuit—The Triode Vacuum Tube—Triode as Detector—Triode as Amplifier—Triode as Timer—Triode as Oscillator—The Generation of Electric Waves—Problems and Questions.

VII. GENERAL PROPERTIES OF X-RAYS 108

Photographic Effect—Fluorescent Effect—Chemical and Dehydrating Effects—Biological Effects—Ionization Effects—Photoelectric Effect—Penetrating Effect—Quality and Tube Voltage—Quality and Half-Value-Layer (H.V.L.)—Homogeneous Beam and Exponential Law—Image Intensifier—Photoelectricity—Photoelectric Timer—Problems and Questions.

VIII. MEASUREMENT OF WAVE LENGTH OF X-RAYS 125

Reflection of X-rays—X-ray Spectrometer—X-ray Spectrograph—Shortest Wave Length—General and Characteristic Radiations—White Radiation—Characteristic Rays—Wave Length and Penetration—*K*, *L*, and *M* Rays—Interpretation of *K*, *L*, and *M* Wave Lengths—Meaning of Corresponding Wave Lengths—Effective Wave Length—Problems and Questions.

IX. RADIOGRAPHY, MICRORADIOGRAPHY AND TOMOGRAPHY 141

Density—Contrast—Meaning of Gamma—Unsharpness—Resolution—Microradiography—Projection Shadow X-ray Microscope—Tomography—Problems and Questions.

X. SECONDARY X-RAYS AND ABSORPTION 150

Secondary X-rays—Scattered Radiation—Characteristic Radiation—Photoelectrons—Seeing Ions—Recoil Electrons and Scattering—Nature of Absorption—Filtration and Critical Absorption Wave Length—The Meaning of Critical Absorp-Wave Length—Absorption Coefficients—Linear Absorption Coefficient and the Exponential Law—Alternative Definition of Linear Absorption Coefficient—Effective Absorption Coefficient—Mass Absorption Coefficient—A Numerical Example—The Coefficients σ and τ—Atomic Absorption Coefficient—The Meaning of Cross-Section—Scattered Rays and Radiography—The Potter-Bucky Diaphragm—Grid Ratio—Lysholm Grid—Problems and Questions.

XI. MEASUREMENT OF DOSAGE FOR ROENTGEN RAYS 177

Quality and Intensity—Intensity and Law of Inverse Square—X-ray Dosage : General Ideas—Saturation Ionization Current—Ionization Chambers—The Roentgen—1937, 1950, and 1953 Definition of the Roentgen—Determination of Effective Volume

CHAPTER PAGE

XI.—contd.

—Electronic Equilibrium—Null Method of Measuring Ionization Current—Thimble Chambers—Victoreen Condenser-Meter—Chamber Walls—Dose-rate Meters—Air Dose, Tissue Dose and Back Scatter—Depth Dosage—Rotational Therapy—Grid and Sieve Therapy—Isodose Curves and Charts—The Roentgen and the Rad—R.E.P.—Integral Absorbed Dose—Energy Flux and the Roentgen—Problems and Questions.

XII. NATURAL RADIOACTIVITY 210

Discovery of Radioactivity—The Nature of the Radiations—Alpha Rays—Beta Rays—Gamma Rays—Internal Conversion Electrons—Auger Electrons—Electron Capture—Geiger-Mueller Counters—Photomultiplier Tube—Scintillation Counter—Radium in Treatment—Strength of a Radioactive Source—Dose in Roentgens—Radon—Average Life—Growth of Radon—The Curie and the Millicurie : Original Meaning—Disintegration and Nature's Transmutation—Meaning of Transformation Constant—Equilibrium and Exact Meaning of Curie—Secular and Transient Equilibrium—Artificial Transmutation—Other Radioactive Families—Problems and Questions.

XIII. PRODUCTION OF HIGH VOLTAGE. PART II. SUPERVOLTAGE TUBES AND HIGH SPEED PARTICLES 248

Importance of Supervoltage—The Cascade Generator—Van de Graaff Generator—Measurement of Supervoltage—Supervoltage Tubes—High Speed Particles—The Cyclotron—The Synchro-cyclotron—The Betatron—The Electron-synchrotron—Proton-synchrotron—Linear Accelerator.

XIV. TRANSMUTATION OF MATTER AND NEUTRONS 273

Nuclear Bombardment—Proton Bombardment—Deuteron Bombardment—Bombardment by Artificial Alpha Particles—Discovery of the Neutron—Production of Neutrons—Energy Classification of Neutrons—Neutron Bombardment—Neutron Capture—Photodisintegration—Detection of Neutrons—Neutron Therapy.

XV. ARTIFICIAL RADIOACTIVITY, MASS AND ENERGY 283

The Positron—Aritificial and Induced Radioactivity—Mass and Energy—Mass of the Neutron—Emission of Gamma Rays in Nuclear Reactions—Pair Production—Medical Uses of Isotopes—Isotopes in Therapy—Isotopes in Diagnosis—Detection and Autoradiography—Basic Physics Necessary in Using Isotopes—Problems and Questions.

XVI. URANIUM FISSION AND NUCLEAR REACTORS 303

Energy from Destruction of Matter and Nuclear Fission—The Chain Reaction—Reactors and Radiology.

PAGE

APPENDIX A. PROTECTION 315

APPENDIX B. SOME USEFUL CONSTANTS AND CONVERSION FACTORS 318

APPENDIX C. TABLE XXIX. ATOMIC NUMBERS AND ATOMIC WEIGHTS 319

INDEX 321

CHAPTER I

ALTERNATING CURRENTS

THE aim of this text is to present in a systematic way the fundamental physical principles utilized in the field of radiology. It is assumed that the reader has had a general course in physics, but the author does not hesitate to review and to amplify important parts of the elementary course. For example, at the outset the student is asked to recall a few principles in electricity and magnetism, that branch of physics whose applications abound in radiology.

1.1. Electromagnetism. All students are familiar with the fact that when a bar magnet is placed beneath a sheet of paper on which iron filings are sprinkled, the filings arrange themselves along regular lines. This simple experiment indicates that in the region around the magnet there is a *magnetic field of force*. To visualize this field we say that it is traversed by magnetic lines or that there is a *magnetic flux* through the medium. At any given place a magnetizing force* acts, producing a *magnetic induction*, which is measured by the *flux density*, that is, by the number of lines of magnetic induction per cm^2, the area being at right angles to the lines. The unit of magnetic induction, that is, 1 line per cm^2 is called the *gauss*. It is invariably the lines of magnetic induction with which we are concerned and usually we speak of a field of either so many lines per cm^2 or so many gauss.

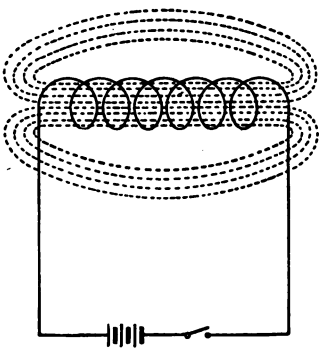


FIG. 1.1. Lines of Force are linked with a solenoidal coil carrying a current.

Elementary experiments with electric currents prove that a magnetic field surrounds a wire carrying a current and show that, if the wire is bent into a solenoidal coil, as in Fig. 1.1, one end of the solenoid is a north pole, the other a south. Moreover, if the air inside the solenoid is replaced by a core of soft iron, the iron becomes strongly magnetized under the influence of the magnetic field due to

* The value of this force is expressed in oersteds, 1 oersted corresponding to a force of 1 dyne acting on a unit magnetic pole, in a vacuum.

the current, and a powerful electromagnet may be created. We can have magnetic fields, therefore, subject to the control of an electric circuit. When the circuit is closed, the magnetic lines are said to be *linked* with the turns of the circuit, the number of *linkages* being equal to the product of the total magnetic flux times the number of turns of the circuit with which they are linked. When the circuit is broken, the lines disappear, with a consequent change in the number of linkages.

1.2. Electromagnetic Induction. Suppose a wire *AB*, Fig. 1.2., which forms part of a simple closed circuit containing a galvanometer *G but no battery*, is free to be moved between the poles of an electromagnet whose circuit is closed. If *AB* is moved from position I across the lines of force to position II, (indicated by *A'B'*) a momentary current is indicated by the galvanometer. If the wire *AB* is moved back again, a momentary current in the opposite direction is recorded.

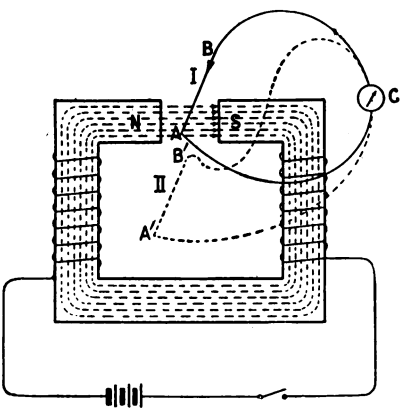


FIG. 1.2. When the wire *AB* is moved across the magnetic field, an induced electromotive force is developed in the wire.

In general, it is found that as long as the wire is moving with respect to the lines of force, a current is developed. This and many other similar experiments prove that *whenever a portion of any circuit is moving with respect to magnetic lines of force, an induced electromotive force (e.m.f.) is developed, and if the circuit is closed, an induced current results.* This is the very important principle of electromagnetic induction, discovered in 1832 by Faraday in England, and simultaneously by Henry in the United States.

The principle may be stated in another and possibly more useful way. When the movable wire *AB* is in position I there are no lines of force linked with the galvanometer circuit, but when it is in position II, all the lines are linked or interlocked with that circuit. Frequently, then, we state that an induced e.m.f. is developed in a circuit wherever there is any *change* in the number of lines linked with it. If, for example, the wire is left in position *A'B'* and the electromagnet circuit (the *primary* circuit) is *broken*, there is a momentary induced current in the movable wire circuit (the *secondary*). Again, when the primary circuit is *made*, a momentary

induced current results in the secondary. In this experiment, the secondary circuit is not moved, but the magnetic lines appear on make of the primary, disappear on break, and so on both make and break there is relative motion of lines and a portion of a circuit. Or, stating it the other way, on *break* of the primary, there is a decrease in the number of lines linked with the secondary ; on *make*, an increase —in both a change, and hence an induced e.m.f. is developed.

The magnitude of the induced e.m.f. is found by experiment to depend on the *rate* at which the lines are cut or on the rate at which the number of linkages is changing. Large e.m.f. may be obtained, therefore, when numerous electric conductors rapidly cut the lines of strong magnetic fields, or when such fields are linked and " unlinked " with many turns of an electric circuit. This, in fact, is the basic principle utilized in dynamos, in transformers and in induction coils.

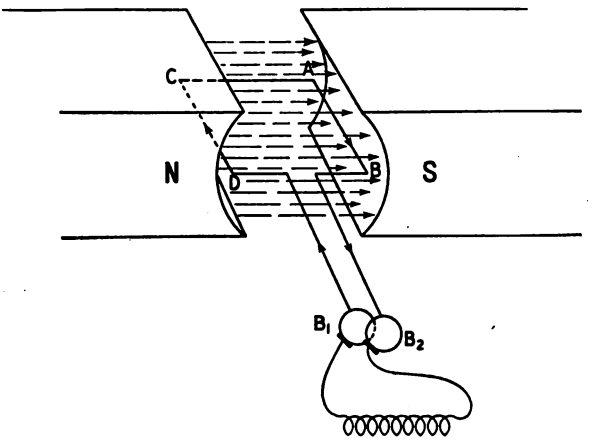


FIG. 1.3. A simple arrangement to generate an alternating current.

1.3. Alternating Currents (a.c.). Suppose a single loop of wire *ABCD*, Fig. 1.3, is rotated in the region between two magnetic poles *N* and *S*. As the wire *AB* goes down it cuts lines of force and in it we have an induced e.m.f. in the direction of the arrow. At the same time *CD*, the other side of the loop, goes up, thus cutting the lines in the opposite direction and so developing in *CD* an induced e.m.f. in the opposite direction. If the ends of the loop are connected to two slip rings upon which rest brushes B_1 and B_2 and these brushes are connected by an external conductor, the circuit is complete and a current flows. Evidently all the time *AB* is going down and *CD* up,

that is, for half a revolution, a current flows in the direction indicated by the arrows. After *AB* has reached its lowest position, however, it begins to move up, thus cutting lines in the opposite direction, and the direction of the induced e.m.f. and of the resulting current reverses. At the same time the wire *CD* reverses its direction from up to down, and in it, too, the induced e.m.f. changes direction. It follows, therefore, that with this simple arrangement, for one half of a revolution a current is flowing in one direction, for the other half, in the opposite.

Not only, however, is there a reversal of current (or, if you like, of polarity between the brushes B_1 and B_2) but the ***strength*** of the current is continually changing. This will be evident if it is realized that when the wire *AB* is passing through its highest position and the wire *CD* through its lowest, each wire is moving parallel to the magnetic lines and hence for a short interval of time there is no cutting and, therefore, no induced voltage and no current. As *AB* goes down (and *CD* up) the lines are cut more and more quickly until after one quarter of a revolution both *AB* and *CD* are moving directly at right angles to the lines. At this instant, therefore, the magnetic lines are cut at the fastest rate and the biggest induced voltage results. For the next quarter of a revolution, the lines are cut less and less quickly until *AB* reaches the bottom (*CD* the top) and once more, for a brief moment, each wire is moving parallel to the lines, and the voltage has dropped to zero again. Evidently, then, during one complete revolution, the current in the circuit will gradually rise in one direction to a maximum value, drop until it is zero, from which it gradually climbs to a maximum in the opposite direction, again falling to zero. If the loop is rotated at steady speed and in a uniform magnetic field, the manner in which the current changes with time is represented graphically in Fig. 1.4. This is called a sine curve, because, as is explained more fully in section 1.11, the changes in current values follow a sine law.

A current of this type is an *alternating* one (a.c.) as well as *sinusoidal.* Obviously a sinusoidal current is characterized by (1) changing polarity and (2) gradual " smooth " changes in intensity.

It is well to note that while a sinusoidal current is always a.c., it is possible to have alternating currents which are not sinusoidal.

Two or three important terms should be noted.

A *cycle* refers to the complete change from zero to a maximum in one direction, down through zero to a maximum in the other direction and back again to zero. In Fig. 1.4, *OA* represents a cycle.

The *frequency* of a.c. is the number of cycles per second. In Britain the frequency is commonly 50 cycles per second, but in the United States and in Canada 60 cycles per second is the usual value.

Neither the voltage nor this frequency could be generated with a simple machine of the type illustrated. In practical a.c. generators or dynamos or alternators found in power houses, the desired frequency and voltage are obtained by using several sets of magnet poles, alternately north and south, and many loops of wire. The fundamental principles utilized, however, are the same as those we have been discussing and the current supplied by such generators generally approximates fairly closely to the sinusoidal.

In direct current (d.c.) generators, it is important to realize that the same principles are utilized and that an alternating e.m.f. is developed in the rotating loops or moving conductors. By the use of commutator plates, this alternating current is *rectified* and direct current flows in the external circuit.

1.4. Strength of a.c. When alternating currents are used in the laboratory, an a.c. ammeter placed in the circuit indicates a definite current of so many amperes. Actually we know that the current is varying in the manner represented by Fig. 1.4, being sometimes in one direction, sometimes in another, with magnitude constantly

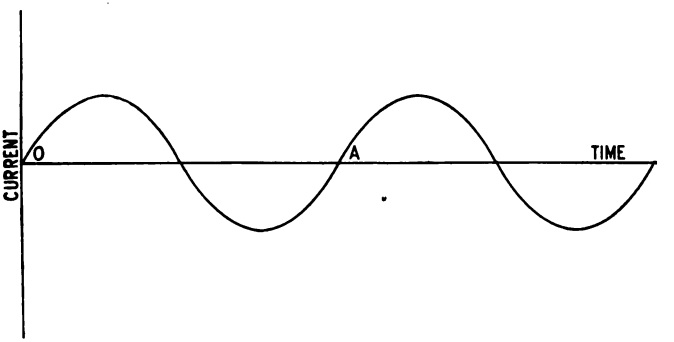


FIG. 1.4. Graphical representation of a simple alternating current.

changing. What, then, does the instrument record ? To understand the answer to that question, it is necessary to know that, by agreement, an alternating current has a value or strength equal to that of a direct current which produces the same heat in a given resistance, in the same time. If, for example, in a certain time an alternating current in a coil of wire develops the same heat as a direct current of

2 amperes, the alternating current has a strength of 2 amperes. Sometimes the strength is said to be so many *virtual* amperes, but more often the qualifying word is dropped.

The common d.c. ammeter of the moving coil type cannot be used to measure alternating current, because with such a current the coil is acted on by rapid impulses tending to rotate it, first in one direction, then in the opposite, and no movement except a possible quivering of the pointer is observed. In a hot wire instrument, however, the movement of the pointer depends on the change in length and tension of a wire heated by a current and this is independent of its direction. Such an instrument, therefore, can be used for measuring both a.c. and d.c. It is, of course, not the only type. For example, there is an instrument which makes use of the magnetism induced in *soft* iron when the current flows in a surrounding coil. By using a fixed piece of iron and a movable one attached to a pivoted pointer, the polarity induced in both pieces at any instant is always the same, regardless of current direction, and the resulting repulsion is a measure of the strength of the current.

1.5. Meaning of r.m.s. The student will recall that the amount of heat developed in a conductor in a given time, depends on the square of the current, or that the power dissipated in a conductor of resistance R is I^2R watts, where I is the current in amperes and R the resistance in ohms. With this in mind it should not be difficult to see that, when alternating current is used, the equivalent direct current is equal to the square root of the average of the squares of successive values, if a complete cycle is subdivided into a large number of intervals. For this reason, the strength of an alternating current or the number of virtual amperes is sometimes referred to as the Root-Mean-Square or r.m.s. value. The same expression may be applied to a similar average of any quantity varying according to the same law as is represented by Fig. 1.4. Alternating voltmeters, for example, record the r.m.s. value of the alternating e.m.f. This should be remembered when, as is often the case, the maximum or peak value of the voltage across an X-ray tube is wanted.

With a little knowledge of calculus, it is not difficult to prove that

$$\text{r.m.s. value} = \frac{\text{maximum value}}{\sqrt{2}}$$

or

$$= 0{\cdot}707 \text{ maximum value.}$$

Thus, if in a.c. ammeter records 7·07 amperes, we know that the actual current changes from 0 to 10 amperes in each direction.

The student should be careful not to confuse r.m.s. with the *average* value, that is, the mean of the current (or voltage) values over half a cycle. In this case we obtain by calculation average value $=\frac{2}{\pi}$ or 0·637 maximum. It should be noted also that the reading on the milliammeter which records the rectified current (*v.* section 6.6) is the average or mean value.

1.6. Inductive and Noninductive Circuits. Suppose a coil of wire is wound around an iron core, as in any ordinary electromagnet, and that it is supplied with direct current. *Before* the circuit is closed, the magnetic field is weak or absent altogether and the number of magnetic lines linked with the circuit is negligibly small. After the circuit is closed, however, a strong magnetic field exists, with a corresponding large number of linkages. *Therefore, during the time immediately following the closing of the circuit*, there is a big change in the number of linkages. Consequently, while the change is taking place, an induced e.m.f., called an *e.m.f. of inductance*, is developed in the coil of the electromagnet.

Now by Lenz's Law, any induced e.m.f. is in a direction opposing the change which gives rise to it. This e.m.f. of inductance, therefore, is in a direction opposite to the original applied voltage, and so immediately after the closing of the circuit, the actual current has a value given by

$$\text{current} = \frac{\text{e.m.f. of battery} - \text{e.m.f. of inductance}}{\text{resistance of circuit}},$$

or, in symbols $I = \frac{E - E'}{R}$, where $E' =$ e.m.f. of inductance.

For this reason the electromagnet current does not immediately attain its final steady value $\left(\text{given by } I = \frac{E}{R}\right)$ but rises somewhat as shown in Fig. 1.5. Ultimately the number of linkages becomes constant, there is no opposing induced e.m.f. and the current has a constant value.

If the electromagnet circuit is *broken*, the lines of force disappear and, if the break is made quickly enough, a large e.m.f. of inductance is developed in the same direction as the original applied e.m.f. Its magnitude may be many times greater than that of the original e.m.f. so great, indeed, that a spark jumps the gap where the break is made. This spark may be accompanied by or followed by an arc between

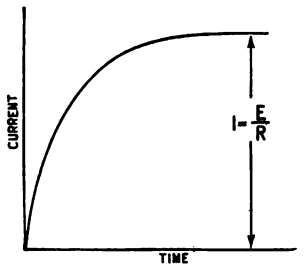


FIG. 1.5. The rise of a direct current in an inductive circuit.

the separated metal parts of the breaking switch, an arc which must sometimes be suppressed by the use of special circuit breakers or magnetic blow-outs.

The effect of inductance* may be illustrated in a simple manner by the use of an ordinary dry cell and an electromagnet (or primary of a transformer) of low resistance. If the terminals of the cell are short-circuited by a piece of copper wire and the circuit suddenly broken, no more than an infinitesimal spark or flash is seen at the place of break. If, however, the cell is connected in series with the electromagnet, on break there is a bright flash. Although the current in the first place is actually greater than in the second, the number of magnetic lines linked with the circuit is so small compared with the number in the second, that the induced e.m.f. on break is not great enough to cause an appreciable spark. With an electromagnet in the circuit, the number of linkages is increased many times and a marked spark occurs when they disappear on break.

This experiment illustrates the difference between a *noninductive* and an *inductive* circuit. In the former, the number of linkages per ampere is so small that the induced e.m.f. on make or on break is negligibly small; in the latter, there is a large number of linkages per ampere, with important effects both on make and on break of a direct current. On make there is a delay in the rise of the current, whereas on break, an e.m.f., often quite large, is developed. A circuit containing an incandescent lamp is noninductive, one with an electromagnet, inductive.

A circuit has an inductance of 1 *henry when the number of linkages per ampere is* 10^8 or *one hundred million.*† For example, if an electromagnet is wrapped with 200 turns of wire and a total flux of 10,000 lines traverses its iron core when the exciting current is 1 ampere, its inductance is

$$\frac{200 \times 10{,}000}{10^8} \quad \text{or} \quad \frac{1}{50} \text{ of a henry.}$$

* The term self-inductance is sometimes used instead of inductance, in order to distinguish this term from what is called mutual inductance. When we are dealing with two adjacent or coupled circuits A and B, the mutual inductance M of circuit B is measured by the number of magnetic lines linked with circuit B due to unit current in circuit A. The unit of mutual inductance is 1 henry as defined in section 1.6.

† One henry is more often defined as the inductance of a circuit such that, when

The student should be careful not to confuse r.m.s. with the *average* value, that is, the mean of the current (or voltage) values over half a cycle. In this case we obtain by calculation average value $=\frac{2}{\pi}$ or 0·637 maximum. It should be noted also that the reading on the milliammeter which records the rectified current (*v.* section 6.6) is the average or mean value.

1.6. Inductive and Noninductive Circuits. Suppose a coil of wire is wound around an iron core, as in any ordinary electromagnet, and that it is supplied with direct current. *Before* the circuit is closed, the magnetic field is weak or absent altogether and the number of magnetic lines linked with the circuit is negligibly small. After the circuit is closed, however, a strong magnetic field exists, with a corresponding large number of linkages. *Therefore, during the time immediately following the closing of the circuit*, there is a big change in the number of linkages. Consequently, while the change is taking place, an induced e.m.f., called an *e.m.f. of inductance*, is developed in the coil of the electromagnet.

Now by Lenz's Law, any induced e.m.f. is in a direction opposing the change which gives rise to it. This e.m.f. of inductance, therefore, is in a direction opposite to the original applied voltage, and so immediately after the closing of the circuit, the actual current has a value given by

$$\text{current} = \frac{\text{e.m.f. of battery} - \text{e.m.f. of inductance}}{\text{resistance of circuit}},$$

or, in symbols $I = \frac{E - E'}{R}$, where $E' =$ e.m.f. of inductance.

For this reason the electromagnet current does not immediately attain its final steady value $\left(\text{given by } I = \frac{E}{R}\right)$ but rises somewhat as shown in Fig. 1.5. Ultimately the number of linkages becomes constant, there is no opposing induced e.m.f. and the current has a constant value.

If the electromagnet circuit is *broken*, the lines of force disappear and, if the break is made quickly enough, a large e.m.f. of inductance is developed in the same direction as the original applied e.m.f. Its magnitude may be many times greater than that of the original e.m.f. so great, indeed, that a spark jumps the gap where the break is made. This spark may be accompanied by or followed by an arc between

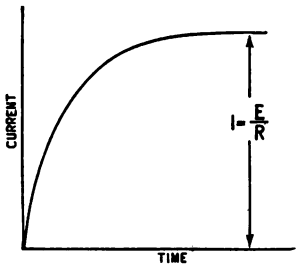


FIG. 1.5. The rise of a direct current in an inductive circuit.

the separated metal parts of the breaking switch, an arc which must sometimes be suppressed by the use of special circuit breakers or magnetic blow-outs.

The effect of inductance* may be illustrated in a simple manner by the use of an ordinary dry cell and an electromagnet (or primary of a transformer) of low resistance. If the terminals of the cell are short-circuited by a piece of copper wire and the circuit suddenly broken, no more than an infinitesimal spark or flash is seen at the place of break. If, however, the cell is connected in series with the electromagnet, on break there is a bright flash. Although the current in the first place is actually greater than in the second, the number of magnetic lines linked with the circuit is so small compared with the number in the second, that the induced e.m.f. on break is not great enough to cause an appreciable spark. With an electromagnet in the circuit, the number of linkages is increased many times and a marked spark occurs when they disappear on break.

This experiment illustrates the difference between a *noninductive* and an *inductive* circuit. In the former, the number of linkages per ampere is so small that the induced e.m.f. on make or on break is negligibly small; in the latter, there is a large number of linkages per ampere, with important effects both on make and on break of a direct current. On make there is a delay in the rise of the current, whereas on break, an e.m.f., often quite large, is developed. A circuit containing an incandescent lamp is noninductive, one with an electromagnet, inductive.

A circuit has an inductance of 1 *henry when the number of linkages per ampere is* 10^8 or *one hundred million.*† For example, if an electromagnet is wrapped with 200 turns of wire and a total flux of 10,000 lines traverses its iron core when the exciting current is 1 ampere, its inductance is

$$\frac{200 \times 10{,}000}{10^8} \quad \text{or} \quad \frac{1}{50} \text{ of a henry.}$$

* The term self-inductance is sometimes used instead of inductance, in order to distinguish this term from what is called mutual inductance. When we are dealing with two adjacent or coupled circuits A and B, the mutual inductance M of circuit B is measured by the number of magnetic lines linked with circuit B due to unit current in circuit A. The unit of mutual inductance is 1 henry as defined in section 1.6.

† One henry is more often defined as the inductance of a circuit such that, when

1.7. Impedance and Inductive Reactance. When an alternating current flows in an inductive circuit, the magnetic field is constantly changing, and so opposing induced e.m.f. are present at all times. These have an important effect on the magnitude of the current in the circuit. Let us examine carefully the difference between an inductive and a noninductive circuit in so far as alternating currents are concerned.

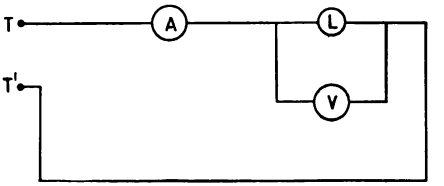


FIG. 1.6. Simple circuit for measuring resistance for d.c. or impedance for a.c.

Suppose a lamp of resistance 440 ohms is joined in series with an ammeter, suitable for either a.c. or d.c., to supply terminals TT', as illustrated in Fig. 1.6. If the supply voltage is 110 direct, the ammeter reads $\frac{110}{440}$ or 0·25 ampere. If the supply voltage is 110 alternating (that is, an a.c. voltmeter placed across the terminals records 110 volts), the ammeter indicates practically the same reading. In other words, Ohm's Law in its simple form holds for both a.c. and d.c. when we are dealing with a simple noninductive circuit.

Now replace the lamp by an electromagnet of resistance 50 ohms and inductance 0·3 henry. With direct current, the ammeter records $\frac{110}{50}$ or 2·2 amperes. With alternating current, the reading is very much less because of the opposing e.m.f. of inductance. Actually the ammeter records about 0·89 amperes. As far as alternating current is concerned, the electromagnet, therefore, has an effective resistance of $\frac{110}{0{\cdot}89}$ or 123·6 ohms. This total resistance to an alternating current is called the *impedance* of the circuit. Its magnitude depends on (1) the true resistance, in this case 50 ohms; and (2) the

the current is changing at the rate of 1 ampere per second, the induced e.m.f. is 1 volt. The two definitions are of course, equivalent.

inductive reactance, the name given to the effective resistance arising from the induced e.m.f.

Since the magnitude of any induced e.m.f. depends on the rate at which the number of linkages is changing, the numerical value of the reactance depends both on the inductance, or the number of linkages per ampere, and on the frequency of the alternating current. Obviously the higher the frequency, the more rapidly the number of linkages is changing. It requires a little mathematics to prove that the reactance in ohms is equal to $2\pi fL$, where f is the frequency and L the inductance expressed in henries.

For example, the reactance of the above electromagnet (whose inductance is 0·3 henry) when an alternating current of 60 cycles per second is used is equal to

$$2\pi \times 60 \times 0{\cdot}3 \quad \text{or} \quad 113{\cdot}1 \text{ ohms.}$$

It will be noticed that, although R the true resistance of the electromagnet is 50 ohms and the reactance 113·1 ohms, the impedance is only 123·6 ohms, not the sum of these two numbers. The problem then arises, given the resistance and the reactance, how can we calculate the impedance? The answer is simple, although the proof is not and must be omitted from this text. If we make a right-angle triangle, as in Fig. 1.7, and let the length of one side represent R the resistance, the other side $2\pi fL$, the reactance, then the impedance is given by the length of the hypotenuse. It follows at once that the impedance Z is given by the relation

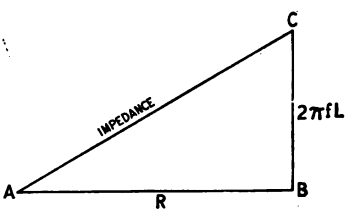


FIG. 1.7. Triangle showing the magnitude of impedance due to resistance and inductive reactance.

$$Z = \sqrt{R^2 + (2\pi fL)^2},$$

which, for the above electromagnet, gives us,

$$Z = \sqrt{50^2 + (113{\cdot}1)^2}$$
$$= 123{\cdot}6 \text{ ohms.}$$

Sometimes the impedance is due almost entirely to the reactance, as in the case of a *choke coil*. This device consists of a coil of wire of low resistance, with an iron core which may be withdrawn from the coil or whose position may be altered in such a way that the value of L the inductance gradually changes.

In high frequency circuits the value of the frequency is of the order of a million or a hundred million cycles per second. With such circuits (and we encounter them in radio sets) even a small value of L may correspond to an appreciable or even a high reactance. For example, if $L=1$ microhenry,* and $f=10^6$ cycles per sec., the reactance is 2π or 6·28 ohms.

1.8. Capacitive Reactance. When a condenser, such as C, Fig. 1.8, is joined to an ordinary battery or to d.c. terminals TT', the condenser is charged, but after a momentary initial current, a good condenser acts as an infinite resistance and an ammeter A placed in the circuit indicates no current. When the condenser is joined to alternating supply terminals, the situation is very different. As the alternating current surges to and fro, the condenser is continually charged and discharged, its plates being alternately positive and negative, negative and positive, and so on. An a.c. ammeter placed in the circuit indicates a current just as if it were in an ordinary lighting circuit.

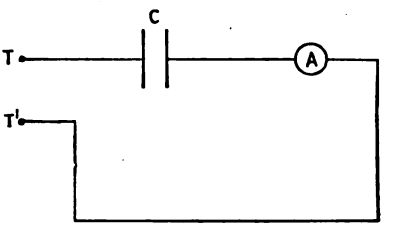


FIG. 1.8. An ammeter in series with d.c. supply and a condenser indicates no current.

If the condenser has a capacitance of 1 microfarad and the alternating supply is 110 volts, 60 cycles per second, the ammeter actually indicates a current of about 0·415 ampere. The condenser, therefore, is equivalent to an effective resistance, or reactance of $\frac{110}{0{\cdot}415}$ or about 265 ohms. This effective resistance is called a *capacitive reactance*, to distinguish it from inductive reactance.

The value of the capacitive reactance may be calculated from the expression $\frac{1}{2\pi fC}$, where C is the capacitance of the condenser expressed in farads.† Taking the above microfarad condenser as an example, we find its reactance to be

$$\frac{1}{2\pi \,.\, 60 \,.\, 1\times 10^{-6}} \quad \text{or} \quad 265 \text{ ohms.}$$

* The student will scarcely need to be reminded that the prefix *micro* means one millionth or 10^{-6} of the main unit.

† The student will recall that, when the potential difference between the plates of a condenser of capacitance 1 farad is equal to 1 volt, the charge on either plate is 1 coulomb.

If f is extremely high, as in diathermy or radio circuits, the capacitive reactance is correspondingly small—just the opposite to the reactance of an inductance for such currents. For example, for a 100 million cycle per second frequency, the reactance of a microfarad condenser is

$$\frac{1}{2\pi \cdot 100 \times 10^6 \times 1 \times 10^{-6}} \quad \text{or} \quad \frac{1}{200\pi}$$

or a small fraction of an ohm.

1.9. Combination of Resistance and Capacitance. If a noninductive resistance, a tungsten lamp, for example, of resistance R ohms is inserted in series with a condenser and the two are joined to a.c. supply terminals, the impedance of the combination is again found by the use of a right-angle triangle. As illustrated in Fig. 1.9, if one side of the triangle represents R, and the other, the capacitive reactance $\frac{1}{2\pi fC}$, the hypotenuse represents the impedance, or, using a formula, the impedance Z of a combination of a noninductive resistance and a condenser is given by

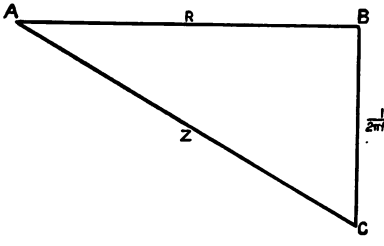


FIG. 1.9. Triangle showing the magnitude of impedance due to resistance and capacitive reactance.

$$Z = \sqrt{R^2 + \frac{1}{(2\pi fC)^2}} \text{ ohms.}$$

1.10. Resistance, Capacitance, and Inductance in Series. When the alternating circuit includes resistance, capacitance, and inductance, the impedance of the circuit is given by

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}.$$

It will be noted that, since in this expression we subtract the two reactances, the impedance may again be found by the use of a right-angle triangle. As before one side represents the value of R, but the length of the other side is now equal to the *difference* between the inductive and the capacitive reactances. In the special case where the two reactances are exactly equal, they cancel one another and the total impedance reduces to R. If R is small, large currents may be

obtained with small alternating voltages. This is an example of what is called *series resonance*, the condition for which is that

$$2\pi fL = \frac{1}{2\pi fC} \quad \text{or} \quad f = \frac{1}{2\pi\sqrt{CL}}.$$

In this type of resonance the current is in tune or in phase with the applied voltage (*v.* section 1.12).

1.11. Parallel Resonance. Sometimes a condenser and a choke coil are inserted in parallel in a circuit, as in Fig. 1.10. To under-

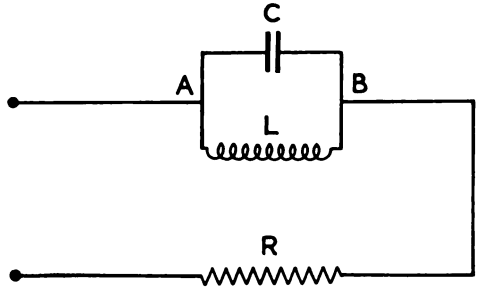


FIG. 1.10. A condenser C and an inductance L inserted in a circuit in parallel.

stand the effect of introducing a combination such as $ACBL$ in a main circuit it is necessary to realize that if the loop (of low resistance) is isolated and by any means the condenser is charged momentarily, an oscillatory discharge will follow, currents surging back and forth with a *natural frequency* given by the resonating condition $f = \frac{1}{2\pi\sqrt{CL}}$.

If the resistance of the loop is negligible and no energy is radiated, such currents may continue for a long time.

Now when such a loop is inserted in a main circuit, as in Fig. 1.10, resonance occurs when the frequency of the applied alternating voltage is exactly equal to this natural frequency. But there is an important difference between series and parallel resonance. Although there may be a large resonating current *in the loop*, the *main* current may be extremely small.*

Now if a small main current results when an appreciable voltage is applied to a circuit of low resistance, the impedance must be *high.* The importance of having a high impedance due to a parallel reson-

* This is because at any given instant the instantaneous currents in the two branches of the loop are out of phase nearly 180°.

If f is extremely high, as in diathermy or radio circuits, the capacitive reactance is correspondingly small—just the opposite to the reactance of an inductance for such currents. For example, for a 100 million cycle per second frequency, the reactance of a microfarad condenser is

$$\frac{1}{2\pi \cdot 100 \times 10^6 \times 1 \times 10^{-6}} \quad \text{or} \quad \frac{1}{200\pi}$$

or a small fraction of an ohm.

1.9. Combination of Resistance and Capacitance. If a noninductive resistance, a tungsten lamp, for example, of resistance R ohms is inserted in series with a condenser and the two are joined to a.c. supply terminals, the impedance of the combination is again found by the use of a right-angle triangle. As illustrated in Fig. 1.9, if one side of the triangle represents R, and the other, the capacitive reactance $\frac{1}{2\pi fC}$, the hypotenuse represents the impedance, or, using a formula, the impedance Z of a combination of a noninductive resistance and a condenser is given by

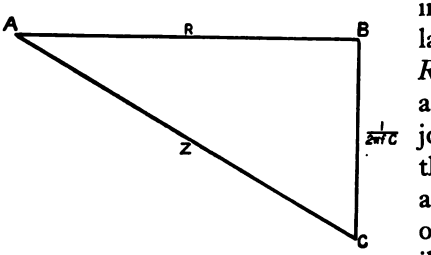


FIG. 1.9. Triangle showing the magnitude of impedance due to resistance and capacitive reactance.

$$Z = \sqrt{R^2 + \frac{1}{(2\pi fC)^2}} \text{ ohms.}$$

1.10. Resistance, Capacitance, and Inductance in Series. When the alternating circuit includes resistance, capacitance, and inductance, the impedance of the circuit is given by

$$Z = \sqrt{R^2 + \left(2\pi fL - \frac{1}{2\pi fC}\right)^2}.$$

It will be noted that, since in this expression we subtract the two reactances, the impedance may again be found by the use of a right-angle triangle. As before one side represents the value of R, but the length of the other side is now equal to the *difference* between the inductive and the capacitive reactances. In the special case where the two reactances are exactly equal, they cancel one another and the total impedance reduces to R. If R is small, large currents may be

obtained with small alternating voltages. This is an example of what is called *series resonance*, the condition for which is that

$$2\pi fL = \frac{1}{2\pi fC} \quad \text{or} \quad f = \frac{1}{2\pi\sqrt{CL}}.$$

In this type of resonance the current is in tune or in phase with the applied voltage (*v.* section 1.12).

1.11. Parallel Resonance. Sometimes a condenser and a choke coil are inserted in parallel in a circuit, as in Fig. 1.10. To under-

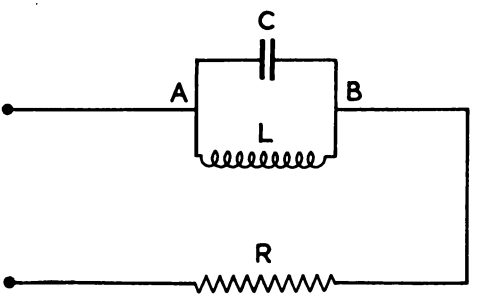


FIG. 1.10. A condenser C and an inductance L inserted in a circuit in parallel.

stand the effect of introducing a combination such as $ACBL$ in a main circuit it is necessary to realize that if the loop (of low resistance) is isolated and by any means the condenser is charged momentarily, an oscillatory discharge will follow, currents surging back and forth with a *natural frequency* given by the resonating condition $f = \frac{1}{2\pi\sqrt{CL}}$.

If the resistance of the loop is negligible and no energy is radiated, such currents may continue for a long time.

Now when such a loop is inserted in a main circuit, as in Fig. 1.10, resonance occurs when the frequency of the applied alternating voltage is exactly equal to this natural frequency. But there is an important difference between series and parallel resonance. Although there may be a large resonating current *in the loop*, the *main* current may be extremely small.*

Now if a small main current results when an appreciable voltage is applied to a circuit of low resistance, the impedance must be *high*. The importance of having a high impedance due to a parallel reson-

* This is because at any given instant the instantaneous currents in the two branches of the loop are out of phase nearly 180°.

ating loop will be seen in the discussion about stabilizers, in section 2.14.

1.12. Phase Difference. The student will recall that when a direct current of I amperes flows under a potential difference of V volts, the power supplied is VI watts. It might be expected that the same expression could be applied when alternating currents are used.

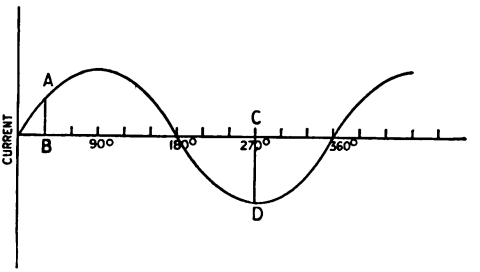


FIG. 1.11. Graph to illustrate the meaning of phase angle.

This, however, is by no means always correct. The power is always *proportional* to the product of V, the voltage recorded by an a.c. voltmeter, times I, the amperage on the a.c. ammeter, but it is not always *equal* to this product. To understand why this is so, it is necessary to explain the meaning of *phase.*

In a sinusoidal curve, such as we have shown in Fig. 1.4 and again in Fig. 1.11, the magnitude at any instant of the changing current (or any other changing variable that the curve represents) can be calculated from the law

$$I = I_m \sin \theta,$$

where I = the magnitude of the current at any instant,
I_m = its maximum value,
and θ = an angle whose value steadily increases with the time and changes in one cycle by 360°.

Suppose, for example, that an alternating current has a maximum value of 10 amperes. Then, to obtain the exact shape of the curve which shows how its magnitude changes during one cycle, all that is necessary is to calculate the values of 10 sin θ for values of θ ranging from 0° to 360° or higher and to plot these values against the corresponding angles. Figure 1.11 is a plot obtained in such a manner.

Now it should be evident that an exact method of describing the particular stage of the cycle which the current (or other variable) has reached at any instant is to give the magnitude of the corresponding angle, or what is called the *phase* angle. Thus at a certain instant

when there is a positive current of magnitude AB, Fig. 1.11, the phase angle is 30°, or when the current has a negative value CD, the phase angle is 270°.

Often we are concerned with the phase difference between two different alternating currents at the same instant, or between the phase angle of the alternating voltage and the corresponding current. It might be thought that at any instant the phase angle of the current would be exactly the same as that of the voltage, but, although that is true in some circuits, it is by no means always so. It is possible, for example, to have the state of affairs represented in Fig. 1.12, where the full line represents the variation in voltage, the dotted line, the corresponding variation in current. It will be noted that when the voltage has a maximum value, the value of the current is zero. In this case, there is a phase difference of 90°, the current lagging behind the voltage by that amount.

Such a phase difference actually exists when we are dealing with an inductance of negligible resistance. If the resistance R cannot be neglected the phase difference between current and voltage (for an inductive resistance) is given by the angle CAB in Fig. 1.7. Calling this angle α, we see at once that its value may be found from the simple relation

$$\cos \alpha = \frac{AB}{AC} = \frac{\text{resistance}}{\text{impedance}}.$$

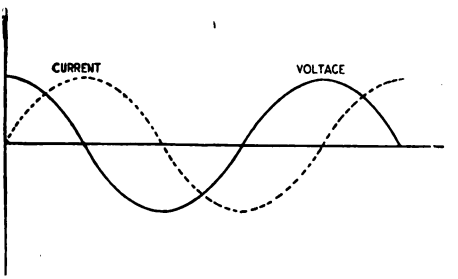


FIG. 1.12. Graphs showing voltage 90° in phase ahead of current.

Thus, in the example worked out in section 1.7, we find the amount the current lags behind the voltage by evaluating α, where

$$\cos \alpha = \frac{50}{123{\cdot}6}.$$

Hence, phase angle = 66° 8′.

In a noninductive circuit, such as one containing an ordinary incandescent lamp, the reactance is negligible, the current and the voltage are in exact step, and there is no difference in phase.

1.13. Power Factor. When alternating current flows in a circuit, *at any instant*, the power in watts = current in amperes × potential difference in volts. The practical problem, however, is to find the average value of this product over a complete cycle. When this is done, we get the expression

$$\text{actual power} = VI \cos \alpha,$$

where V = voltage recorded by a.c. voltmeter,
I = current recorded by a.c. ammeter,
and α = phase difference between current and voltage.

The following three different cases should be noted :

(*a*) A noninductive circuit.

Here $\alpha = 0°$ or the current and the voltage are in step, and the power $= VI$ watts, as in d.c.

(*b*) An inductance of very small resistance.

In this case α is very nearly equal to 90°, $\cos \alpha = 0$, and the power $= 0$, which means that actually there is no power loss in a reactance, such as a *choke coil*, if the resistance is sufficiently low. This apparently strange result means that the energy stored in the surrounding medium (the magnetic field) in one part of the cycle, returns to the circuit in another. A circuit or portion of a circuit to which this applies is said to be *wattless*. It is for this reason that a choke coil is a more efficient way of changing the strength of an alternating current than an ordinary rheostat in which the power is dissipated as heat.

In a practical choke coil some such device as changing the position of an iron core, enables the operator to alter gradually the magnitude of the inductance and so gradually to vary the current.

(*c*) An inductive resistance, such as an ordinary electromagnet or the primary of a transformer.

As an illustration, consider an electromagnet, of resistance 50 ohms and inductance 0·3 henry, attached to a supply voltage of 110, a.c. As we have already seen on pages 9 and 15, the impedance is 123·6 ohms, the current 0·89 amperes, and the phase difference between current and voltage 66° 8′. Hence, the power dissipated in the electromagnet

$$= 110 \times 0{\cdot}89 \times \cos 66° \, 8'.$$
$$= 110 \times 0{\cdot}89 \times 0{\cdot}4045$$
$$= 39{\cdot}6 \text{ watts.}$$

The value of $\cos \alpha$ (in this example about 0·4) is called the *power factor*. It will be seen that unless its magnitude is known, we cannot find the actual power consumed by an inductive circuit.

The student will realize that instead of using the phase angle, the power factor can be found at once from the ratio $\frac{\text{resistance}}{\text{impedance}}$; or, in the above example, it is equal to $\frac{50}{123{\cdot}6}$.

When energy is dissipated in a resistance heat is developed. The student should recall that the energy dissipated or consumed in t seconds is equal to VIt or I^2Rt watt-seconds or joules for d.c. and $VIt \cos \alpha$ for a.c. He should recall also that

$$1 \text{ calorie} = 4{\cdot}2 \text{ joules.}$$

1.14. Capacitance and Phase Difference. When a circuit attached to an a.c. supply contains capacitance and a negligible resistance, there is again a phase difference between current and voltage, but this time the current is 90° *ahead* of the voltage. If the resistance is not negligible, the phase angle by which the current leads the voltage is less than 90°, being in fact equal to the angle BAC in the triangle of Fig. 1.9.

As far as phase difference is concerned, it is important to realize that inductance and capacitance have opposite effects, current lagging because of inductance, leading because of capacitance. Hence, in a circuit containing resistance, capacitance and inductance, we may have current either lagging or leading, or, in the special case where the inductive reactance is equal to the capacitive reactance, the current is in

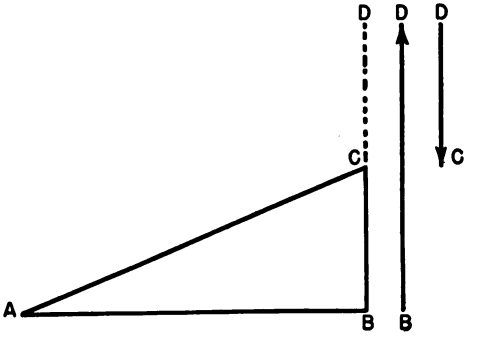


FIG. 1.13A. Combination of inductive and capacitive reactance. BD represents the inductive reactance, DC the capacitive reactance, AC the impedance.

In a noninductive circuit, such as one containing an ordinary incandescent lamp, the reactance is negligible, the current and the voltage are in exact step, and there is no difference in phase.

1.13. Power Factor. When alternating current flows in a circuit, *at any instant*, the power in watts = current in amperes × potential difference in volts. The practical problem, however, is to find the average value of this product over a complete cycle. When this is done, we get the expression

$$\text{actual power} = VI \cos \alpha,$$

where V = voltage recorded by a.c. voltmeter,
I = current recorded by a.c. ammeter,
and α = phase difference between current and voltage.

The following three different cases should be noted :

(*a*) A noninductive circuit.

Here $\alpha = 0°$ or the current and the voltage are in step, and the power $= VI$ watts, as in d.c.

(*b*) An inductance of very small resistance.

In this case α is very nearly equal to 90°, $\cos \alpha = 0$, and the power $= 0$, which means that actually there is no power loss in a reactance, such as a *choke coil*, if the resistance is sufficiently low. This apparently strange result means that the energy stored in the surrounding medium (the magnetic field) in one part of the cycle, returns to the circuit in another. A circuit or portion of a circuit to which this applies is said to be *wattless*. It is for this reason that a choke coil is a more efficient way of changing the strength of an alternating current than an ordinary rheostat in which the power is dissipated as heat.

In a practical choke coil some such device as changing the position of an iron core, enables the operator to alter gradually the magnitude of the inductance and so gradually to vary the current.

(*c*) An inductive resistance, such as an ordinary electromagnet or the primary of a transformer.

As an illustration, consider an electromagnet, of resistance 50 ohms and inductance 0·3 henry, attached to a supply voltage of 110, a.c. As we have already seen on pages 9 and 15, the impedance is 123·6 ohms, the current 0·89 amperes, and the phase difference between current and voltage 66° 8′. Hence, the power dissipated in the electromagnet

$$= 110 \times 0{\cdot}89 \times \cos 66° \, 8'.$$
$$= 110 \times 0{\cdot}89 \times 0{\cdot}4045$$
$$= 39{\cdot}6 \text{ watts.}$$

The value of cos α (in this example about 0·4) is called the *power factor*. It will be seen that unless its magnitude is known, we cannot find the actual power consumed by an inductive circuit.

The student will realize that instead of using the phase angle, the power factor can be found at once from the ratio $\frac{\text{resistance}}{\text{impedance}}$; or, in the above example, it is equal to $\frac{50}{123{\cdot}6}$.

When energy is dissipated in a resistance heat is developed. The student should recall that the energy dissipated or consumed in t seconds is equal to VIt or I^2Rt watt-seconds or joules for d.c. and $VIt \cos \alpha$ for a.c. He should recall also that

$$1 \text{ calorie} = 4{\cdot}2 \text{ joules.}$$

1.14. Capacitance and Phase Difference. When a circuit attached to an a.c. supply contains capacitance and a negligible resistance, there is again a phase difference between current and voltage, but this time the current is 90° *ahead* of the voltage. If the resistance is not negligible, the phase angle by which the current leads the voltage is less than 90°, being in fact equal to the angle BAC in the triangle of Fig. 1.9.

As far as phase difference is concerned, it is important to realize that inductance and capacitance have opposite effects, current lagging because of inductance, leading because of capacitance. Hence, in a circuit containing resistance, capacitance and inductance, we may have current either lagging or leading, or, in the special case where the inductive reactance is equal to the capacitive reactance, the current is in

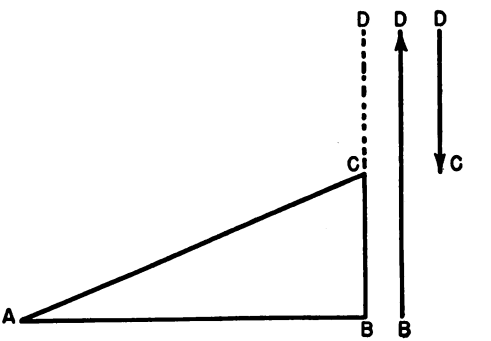


FIG. 1.13A. Combination of inductive and capacitive reactance. BD represents the inductive reactance, DC the capacitive reactance, AC the impedance.

phase with the voltage. The three cases are represented graphically in the diagrams of Figs. 1.13A, 1.13B, and 1.13C. In each of these figures, the resistance is represented by *AB*, the inductive reactance by *BD*, the capacitive reactance by *DC*, and the impedance by *AC*. In Fig. 1.13C, where the inductive reactance is equal to the capacitive reactance, *AC* represents both the resistance and the impedance, and we have the conditions for resonance to which reference was made at the end of section 1.10.

It follows that α, the phase difference between current and voltage, may be made any desired value by suitably varying capacitance and inductance. This is of importance when it is desired to reduce

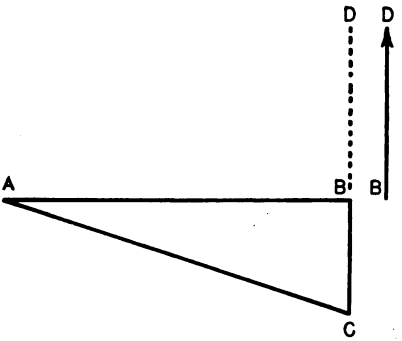


FIG. 1.13B. Same as Fig. 1.13A, except that the capacitive reactance is greater than the inductive.

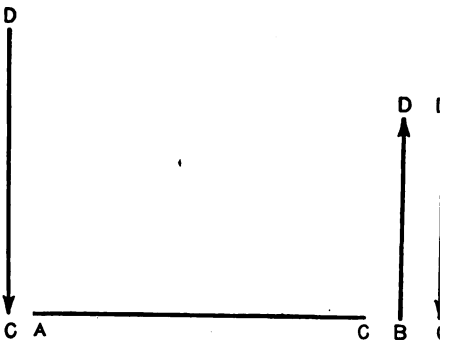


FIG. 1.13C. In this case, the capacitive reactance is equal to the inductive.

power loss. If a given amount of power—so many watts—is to be supplied at a fixed voltage, evidently, since power supplied $= VI \cos \alpha$, the larger the power factor (or the smaller α), the smaller the current necessary. Since power loss due to resistance is I^2R watts, smaller currents mean smaller power losses.

PROBLEMS AND QUESTIONS

1. Describe a simple experiment to illustrate the difference between an inductive and noninductive circuit.

2. Describe, with reference to a simple experiment, the meaning of the inductance of a circuit. What effect has a high inductance when a direct voltage is applied?

3. When 110 volts d.c. are applied to the terminals of an electromagnet, the current is 2·5 amp ; whereas when 110 volts a.c. are applied the current is only 0·8 amp. Explain clearly the reason for the difference.

4. An electromagnet has a resistance of 30 ohms and a reactance of 40 ohms (for a.c. of 60 cycles per sec.). Find (i) the impedance of the electromagnet, (ii) the inductance in henries. *Ans.* (i) 50 ohms ; (ii) 0·106 henry.

5. Distinguish between impedance and resistance.

6. When 60 cycles per sec. a.c. is used, the impedance of a coil is found to be 40 ohms. If the resistance of this coil is 10 ohms, find its inductance in henries. *Ans.* 0·103.

7. The reactance of a coil when used with 60 cycles per sec. a.c. is 50 ohms. Find its inductance. *Ans.* 0·13 henry.

8. When 110 volts *alternating* are applied to an electromagnet of resistance 30 ohms an a.c. ammeter in the circuit records 0·5 amp. Find : (i) the impedance of the electromagnet, (ii) its reactance, and (iii) its inductance (in henries), if the a.c. is 60 cycles per second. *Ans.* (i) 220 ohms ; (ii) 217·9 ohms ; (iii) 0·58.

9. When 110 volts alternating, frequency 60 cycles per second, is applied to a coil with some resistance and with inductance equal to 1/10 henry, the resulting current is 2·0 amp. Find the current when 110 volts direct is applied to the same coil. *Ans.* 2·75 amp.

10. (*a*) When a flat circular coil of 2,000 turns, with a mean radius of 5 cm, carries a direct current of 1 amp, the magnetic field inside the coil has a mean value of 50 gauss. Assuming the field to be uniform, calculate the number of linkages for this current, and hence the inductance of the coil (in henries). (*b*) If this coil had negligible resistance and 110 volts, 60 cycle per sec. alternating, is applied to it, find the current. *Ans.* (*a*) $7{\cdot}85 \times 10^6$, 0·078 ; (*b*) 3·7 amp.

11. When a coil of resistance 40 ohms is joined to a supply of 110 volts, alternating, an a.c. meter in the circuit records 2·0 amp. Find : (i) the inductive reactance of the coil ; (ii) its inductance, if the frequency of the a.c. is 60 cycles per second ; (iii) the number of linkages when the coil carries a steady current of 2 amp.

12. An incandescent lamp and an electromagnet are joined in series across terminals between which there is a p.d. of : (i) 110 volts direct ; (ii) 110 volts alternating. In which case is the lamp the brighter? Explain your answer.

13. If the electromagnet in 12 is replaced by a condenser of fairly large capacitance what difference is now observed?

14. One hundred and ten volts, direct, are applied to an electromagnet whose true resistance is 55 ohms. Find : (i) the final steady current, (ii) the back e.m.f. (or e.m.f. of inductance) at the instant the current, just after the circuit has been closed, has reached the value 1 amp. *Ans.* 55 volts.

15. One hundred and ten volts, alternating, are applied to a coil of many turns, whose inductance is 1 henry and resistance 11 ohms, joined in series with a condenser of capacitance of 25 microfarads. (*a*) Calculate for what frequency the inductive reactance is equal to the capacitive reactance. (*b*) Calculate the current for this frequency. *Ans.* (*a*) 31·8 cycles per sec. ; (*b*) 10 amp.

16. A non-inductive resistance of 75 ohms and a coil of negligible resistance with inductance $\frac{1}{\pi}$ henry are connected in series to 250 volt a.c. supply

terminals, the frequency being 50 cycles per second. Find (*a*) the current; (*b*) the power taken from the mains; (*c*) if a condenser is inserted in series with the resistance and the coil, what capacitance it must have to bring the current in phase with the supply voltage. *Ans.* (*a*) 2 amps; (*b*) 300 watts; (*c*) 31·8 mf.

17. What is the peak voltage across 220 volt a.c. supply mains? If in a circuit attached to these mains, an ammeter registers 8 amps, find: (*a*) the maximum value of the current; (*b*) the average value.

18. A coil of 10 ohms resistance, which is connected across 230 volt a.c. mains is found to carry a current of 5 amperes. Find: (*a*) the impedance of the circuit; (*b*) the reactance; (*c*) the power taken from the mains. *Ans.* (*a*) 46 ohms; (*b*) 44·9 ohms; (*c*) 250 watts.

19. When a resistance of 50 ohms is connected in series with an inductance of 20 millihenry and a condenser across 200 volt a.c. mains, the resulting current is 4 amperes. (*a*) If the frequency of the a.c. is 150 cycles per second, find the capacitance of the condenser. (*b*) If the frequency is doubled, with no change in the supply voltage, find: (i) the current, (ii) the power factor, (iii) the voltage across each component of the circuit, (iv) the total power consumed.

20. A choke coil is found to take a current of 10·5 amps when connected in series with a 5 mf condenser across 230 volt a.c. mains, frequency 50 cycles per second. When the choke coil is connected directly across 210 volt d.c. mains, the current is 10·5 amps. If when a.c. is used the current leads the applied voltage, find: (*a*) the power factor, (*b*) the inductance of the choke coil. *Ans.* (*a*) 0·67; (*b*) 0·028 henry.

21. In an inductive circuit carrying a.c., when the supply voltage is 200 V at 50 cycles per second, the current is 5 amps and 800 watts are dissipated. (*a*) Find (i) the impedance, (ii) the resistance, (iii) the reactance. (*b*) If a condenser is added in series to make the circuit resonant, find: (i) the capacitance of the condenser, (ii) the current. *Ans.* (*a*) (i) 40 ohms; (ii) 32 ohms; (iii) 24 ohms. (*b*) (i) 133 mf; (ii) 6·25 amps.

22. A choke coil is found to take a current of 10·5 amps when connected directly to 210 volt d.c. supply mains *or* when connected in series with a 5 mf condenser to a.c. supply mains of 210 volts and frequency 50 cycles per second. If the alternating current leads the applied voltage, calculate: (*a*) the inductance of the choke coil, (*b*) the power factor.

23. A choke coil is found to take 6 amps when connected across 240 volt d.c. mains, but only 1 amp when across 240 volt a.c. of 50 cycles per second. (*a*) How would you make this coil take a lagging current from the same a.c. supply at a power factor of 0·667? (*b*) After the change, find: (i) the voltage across the coil, (ii) the power taken from the mains.

24. (*a*) Find the inductance of a choke coil which carries 7 amps when connected across 210 volt d.c. mains, but only 1 amp when across 210 volt a.c. of 50 cycles per second. (*b*) What change would you make in the circuit to make the alternating current 3 amps?

CHAPTER II

PRODUCTION, MEASUREMENT AND CONTROL OF HIGH VOLTAGE.

Part I

To operate any type of X-ray tube, a voltage very much in excess of those encountered in ordinary circuits must be available. Actual values range from less than 10,000 to more than 1,000,000 volts. In this chapter, our attention is confined to means of obtaining potential differences which do not exceed 200,000 or 250,000 volts.

2.1. The Transformer. For voltages up to about a quarter of a million, the common device used in X-ray outfits is the transformer. Here the principle is that of electromagnetic induction. In Fig 2.1, *ABCD* represents a series of sheets of soft iron put together to form a core of the shape illustrated. A coil of wire *P*, the primary, connected to an alternating source of potential difference, is wrapped about one arm of the iron core, while a second coil *S*, the secondary, is wrapped about another part (or overlapping the primary). When the primary circuit is closed, the resulting magnetic field is continuously changing, the number of lines rising to a maximum in one direction, then decreasing to zero, then increasing in the opposite direction. Whenever the number of linkages is increasing,* there is an induced e.m.f. in the secondary in one direction, but when the number is decreasing (or increasing with the lines reversed) the e.m.f. is in the opposite direction. The induced voltage in the secondary, therefore, is alternating and of the same frequency as that of the primary current, the relation between the two being somewhat as shown in Fig. 2.2.

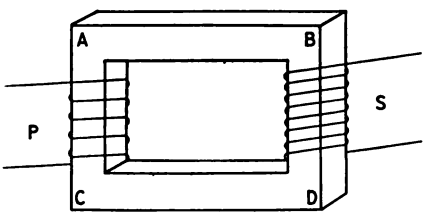


FIG. 2.1. Primary and secondary of a simple closed core transformer.

The magnitude of the secondary e.m.f. is approximately as many times greater (or less) than the primary voltage as the total number of turns in the secondary is greater (or less) than the number in the

* An increase of lines in one direction has the same effect as a decrease of lines in the opposite direction.

primary. To understand why this is so, it is necessary to realize that there is an induced e.m.f. (the e.m.f. of inductance discussed in section 1.6) in the primary coil itself and that, when the secondary circuit is open so that no power is taken from the transformer, the only function of the primary current is to maintain the alternating magnetic field. Only a small current is necessary for this. If the primary resistance is small, the actual voltage necessary to maintain the current is very small also and therefore the e.m.f. of inductance is almost equal to the applied voltage, just as when a direct current motor is running freely without any external load, the back e.m.f. in

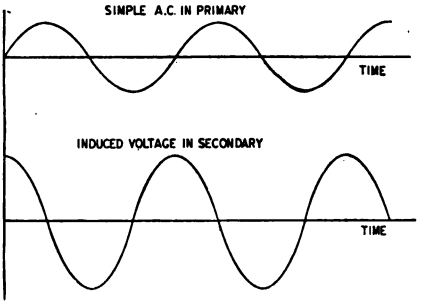


FIG. 2.2. Graphical representation of current in primary of a transformer and of corresponding induced voltage in secondary.

the armature is almost equal to the applied voltage. Now since the same lines of force cut each turn of both primary and secondary, the induced e.m.f. per turn in the secondary must be equal to the induced e.m.f. per turn in the primary. Hence,

$$\text{resultant secondary e.m.f.} = \text{e.m.f. of inductance in primary} \times \frac{\text{number of turns in secondary}}{\text{number of turns in primary}}.$$

Therefore, since applied voltage across primary is nearly = e.m.f. of inductance, we may write with little error,

$$\text{e.m.f. in secondary} = \text{primary voltage} \times \frac{\text{number of turns in secondary}}{\text{number of turns in primary}}.$$

Thus, if 110 volts are applied to the primary of a transformer for which the ratio of secondary to primary is 1,000, the secondary e.m.f. is about 110,000 volts.

The secondary e.m.f. may be either higher or lower than the primary voltage. In a *step-down* transformer, such as is used for heating the filament of an X-ray tube (section 5.4) or a rectifying valve (section 5.3), the voltage is lowered. In *step-up* transformers,

the secondary voltage is greater, and as we have already seen, may reach or exceed 250,000 volts.

2.2. Insulation. As the high tension voltage becomes greater, the problem of good insulation becomes more difficult. Injurious sparking may occur between different parts of the secondary or between the secondary and its surroundings. At one time some X-ray transformers were impregnated with wax, but this method proved unsatisfactory even for only moderately high voltages. Air bubbles developed and sparking took place through the cavities thus formed. Good high tension transformers are now immersed in oil, a method which not only provides better insulation but has the further advantage that because of convection currents heat is dispersed more rapidly.

The centre of the secondary coil is frequently joined to earth.

2.3. Efficiency and Power Rating of Transformers. When the secondary circuit is closed, a current flows and power is delivered to this circuit. Automatically* more power is delivered by the supply source to the primary. The transformer, therefore, may be looked on as a mechanism for receiving power at one voltage and current and delivering it at a different voltage and current. Inevitably there is some loss in the transaction, although a good transformer may have an efficiency greater than 95 per cent. The energy losses may be grouped under two headings: (*a*) iron losses; (*b*) copper losses. Under (*a*) we include (i) the loss due to hysteresis, arising from the magnetizing and demagnetizing of the iron core, and (ii) the loss due to eddy currents in the mass of the metal. The former loss is reduced by choosing a type of iron in which the magnetism lags behind the magnetizing field as little as possible; and the latter loss by the use of laminated cores.

Copper loss is the name given to the heat loss arising from the resistance of the wire carrying the current. The magnitude of this is equal to I^2R watts, where I is the customary symbol for the current in amperes, and R the resistance in ohms.

Even when all these losses are kept to a minimum, high efficiency is not obtained unless the primary and secondary coils are more closely coupled than they are in Fig. 2.1. Good coupling is obtained by winding the primary and the secondary close together, but as the

* The complete explanation of the reason for this is not simple, but a general idea may be had from the following. By Lenz's Law any induced current opposes the movement of the magnetic lines which cause it. Therefore, the secondary current will oppose the changing magnetic flux. If lines are on the increase, it will create a counterfield opposing the increase. This reduction in flux will lessen the opposing e.m.f. of inductance in the primary, and hence the primary current will automatically increase.

aim of this text is to explain principles rather than technical details, exact methods of constructing transformers will not be described.

In ordinary problems it is usual to assume that the transformer is 100 per cent efficient. The following example may be useful.

In a step-up transformer, the secondary has 1,000 *times as many turns as the primary. If* 10 *milliamperes are delivered at* 100,000 *volts, find* (i) *the primary current*, (ii) *the primary voltage.*

Since the secondary e.m.f. is 100,000 volts, and the ratio of the number of turns in secondary to that in primary is 1,000,

$$\text{primary voltage} = \frac{100{,}000}{1{,}000} = 100 \text{ volts.}$$

If the transformer is 100 per cent efficient, then primary voltage × primary current = secondary voltage × secondary current, or

$$100 \times I_p = 100{,}000 \times \cdot 010$$

or

$$I_p = 10 \text{ amperes.}$$

Or, alternately, we may find the primary current at once, from the fact that, if the secondary voltage is 1,000 times greater than that applied to the primary, the secondary current must be 1,000 times less. Hence,

$$\text{primary current} = 0{\cdot}010 \times 1{,}000 = 10 \text{ amperes.}$$

2.4. Inherent Regulation. It is important to realize that the voltage across the terminals of the secondary of a transformer when a secondary current or " load " is being delivered is less than the voltage across the terminals in open circuit. In the problem solved in the previous section, the secondary e.m.f. is 100,000 volts, but the voltage across the terminals would be less than this amount by the drop in voltage due to the resistance of the secondary coil. For example, if this resistance was 10,000 ohms, for a current of 10 ma there would be a voltage drop of $0{\cdot}010 \times 10{,}000$ or 100 volts and the potential difference across the secondary terminals would be 99,900 volts. For a secondary current of 100 ma the potential difference would be 99,000, and so on.

The term *inherent regulation* has reference to this point. It is measured by the difference between the peak secondary voltage at no load (open circuit) and the peak voltage at a rated load, divided by the peak secondary voltage at no load. It is usually expressed as a percentage. Thus, using the above data, the regulation for a load of 100 ma is 1 per cent.

The specifications of the British Standards Institution state that

for diagnostic work, the inherent regulation of transformers for momentary rating (see next section) shall not exceed 25 per cent; for treatment at continuous rating the regulation " shall not exceed 10 per cent unless the apparatus includes condensers for smoothing or voltage multiplying purposes, in which case a voltage drop not exceeding 25 per cent is permissible ".

2.5. Transformer Rating. The maximum permissible power supplied by an X-ray transformer depends on the length of time current is flowing. The British Standards Institution specifies transformer rating under two conditions: (*a*) for continuous use; (*b*) for momentary use, that is, for a period not exceeding 1 second with a rest period of 1 minute. One firm* has added a third category called a " short " period, one with the current on for a time not exceeding 30 seconds, off for intervals 5 times as long. For example, a certain transformer was advertised as having an output of 120,000 volts peak at 25 ma for continuous use; or 110,000 volts at 60 ma for a short time; or 100,000 volts at 100 ma for momentary use.

In operating roentgen tubes it is highly important not only to be able to vary the voltage applied to the tube, but also to know its actual magnitude. In the following sections important methods of doing these things are discussed. Reference is first made to several methods of measuring high voltages.

2.6. Spark-gap Meter. The principle of this method is extremely simple—the greater the potential difference between two conductors, the longer the spark between them when the air insulation breaks down. Spark lengths may thus be equated to corresponding voltages, but in doing so one or two precautions must be considered. To begin with, the spark length depends on the shape and size of the conductors, as well as the potential difference between them. The same voltage gives a different length between two pointed than between two spherical conductors, and still different if one conductor is a sharp point, the other a plane. The length even varies for spherical conductors of different diameters, as will be seen by a glance at Table I (taken from Kaye and Laby's Tables).†

It will be noted that the lengths given in this table are for air at 25° C. and 760 mm pressure. For different values of both temperature and pressure, a correction must be made because these factors also affect the spark length for a given voltage. Table II, for example,

* Watson & Sons (Electro-Medical) Ltd., London.

† *Physical and Chemical Constants and Some Mathematical Functions*, by G. W. C. Kaye and T. H. Laby. Longmans, Green and Co.

gives the correction which must be applied to the values given in Table I, for a few other temperatures and pressures. To illustrate, with spheres of diameter 10 cm, at a pressure = 740 mm, and temperature = 20° C., the voltage corresponding to a spark length of 2·02 cm, is not 60,000 but 60,000 × 0·99.

To some extent the spark-over voltage depends also on the humidity of the air, and for highly accurate work correction has to be made for this factor. A. B. Lewis has shown that, for voltages of the order of 10,000, there is an increase in spark-over voltage, for a fixed gap, amounting to 0·13 per cent for each millimeter of vapour pressure of water in the atmosphere.

TABLE I

SPARKING VOLTAGES AT 25° C. AND 760 MM PRESSURE

Kilo Volts (Peak)	Needle Points No. 00 New Sewing Needles		Spheres		
			Diameter 5 cm	Diameter 10 cm	Diameter 25 cm
	cm gap	inches gap	cm gap	cm gap	cm gap
10	—	—	0·29	0·30	0·32
15	1·30	0·51	0·44	0·46	0·48
20	1·75	0·69	0·60	0·62	0·64
25	2·20	0·87	0·77	0·78	0·81
30	2·69	1·06	0·94	0·95	0·98
35	3·20	1·26	1·12	1·12	1·15
40	3·81	1·50	1·30	1·29	1·32
45	4·49	1·77	1·50	1·47	1·49
50	5·20	2·05	1·71	1·65	1·66
60	6·81	2·68	2·17	2·02	2·01
70	8·81	3·47	2·68	2·42	2·37
80	—	—	3·26	2·84	2·74
90	—	—	3·94	3·28	3·11
100	—	—	4·77	3·75	3·49
110	—	—	5·79	4·25	3·88
120	—	—	—	4·78	4·28
130	—	—	—	5·35	4·69
140	—	—	—	5·97	5·10
150	—	—	—	6·64	5·52
160	—	—	—	7·37	5·95
170	—	—	—	8·16	6·39
180	—	—	—	9·03	6·84
190	—	—	—	10·0	7·30
200	—	—	—	11·0	7·76
210	—	—	—	—	8·24
220	—	—	—	—	8·73
230	—	—	—	—	9·24
240	—	—	—	—	9·76
250	—	—	—	—	10·3

TABLE II

Temp.	Pressure, 720 mm	Pressure, 740 mm	Pressure, 760 mm	Pressure, 780 mm
0°	1·04	1·06	1·09	1·12
10	1·00	1·02	1·05	1·08
20	0·96	0·99	1·02	1·04
30	0·93	0·96	0·98	1·01

In actual use a spark-gap meter with spheres of a standard size is placed across the terminals of the tube, as shown in Fig. 2.3. With the tube running, the distance between the gap terminals is gradually lessened until a spark takes place. To protect the surfaces of the spheres from injury due to excessive sparking, series resistances *RR* of many thousand ohms should be placed as illustrated. It is important to note that a current should actually be flowing through the tube when the reading is taken. If no current is in the tube circuit, the length of the spark measures the e.m.f. or maximum voltage got up by the transformer. (See again section 2.4.)

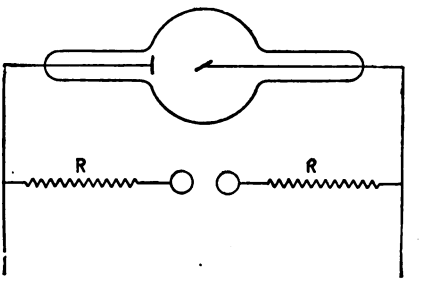


FIG. 2.3. Sphere gap, with protecting resistors, for measurement of voltage across an X-ray tube.

2.7. Corona. Before leaving the subject of sparking potentials, attention is directed to the difference between a spark and *corona* or *brush* discharge. In the case of a spark the electric field between two conductors (one of which may be the earth) becomes so intense that the air resistance breaks down along what is practically a continuous path between them. A discharge passes, accompanied by a crackling sound and marked luminosity. If a conductor is at high potential, the air in its immediate vicinity may become conducting without a complete breakdown between it and another conductor. In this case, a feeble discharge takes place, accompanied by a glow called the *corona*, which can be seen in a darkened room. The smaller the dimensions of the conductor, the more the likelihood of a corona discharge. In the early days of roentgenology, the high tension leads running to the X-ray tube were frequently narrow wires which were wound on a small reel. With these marked corona was a common experience. Corona is undesirable, because it means not only a loss

of energy, but also the danger of the formation of undesirable ozone and oxides of nitrogen. It can be avoided, as it now invariably is, by the use of conductors of large size, kept well apart and well away from the earth.

2.8. Primary Voltmeter. The most common and certainly the most convenient, if not the most accurate, method of measuring the potential difference across the terminals of a tube consists in the use of an ordinary a.c. voltmeter across the primary terminals of the transformer. The higher the primary voltage, the greater the e.m.f. in the secondary and the greater the voltage across the tube. Hence in any given outfit, the scale of the voltmeter may be marked to read tube voltage instead of the primary voltage which it really records. Unfortunately the scale can be exact for only one value of the tube current. It is true that for each primary voltage, there is a corresponding e.m.f. induced in the secondary, but, as we have already noted, when a current is flowing in the tube circuit, the potential difference across the tube terminals is less than the e.m.f. because of the voltage drop in the secondary winding. Now this voltage drop depends on the current, being greater the greater the current, hence for the same primary reading of the voltmeter the potential difference across the tube will decrease as the tube current increases. For example, in a certain X-ray transformer, for a primary voltage of 80, a spark-gap meter across a tube gave a reading of 3·06 inches for a tube current of 10 ma, but only 2·85 inches for a current of 30 ma; or, for a primary reading of 100 volts, the spark length was 4·51 inches for 10 ma, but only 4·10 inches for 30 ma.

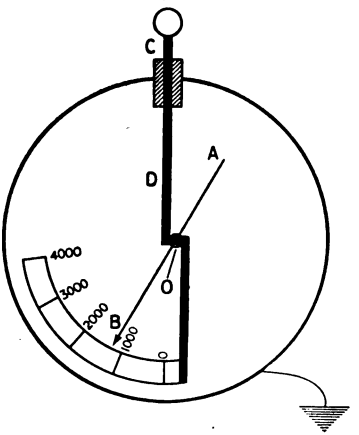


FIG. 2.4. The Braun electrostatic voltmeter.

For very exact work, therefore, it would be necessary to have a separate scale on the primary voltmeter for each tube current. If the tube is to be used with only a narrow range of currents, this is not necessary; and, in any case, a primary voltmeter calibrated to read tube kilovolts for a single milliamperage is an extremely useful feature of an X-ray transformer outfit. Frequently all that an operator wishes is to operate his tube at the same voltage as used previously, with the same tube current.

2.9. Electrostatic Voltmeter. An ordinary " gold-leaf " electroscope is an electrostatic voltmeter, the deflection of the leaf measuring the potential difference between the charged system and the surrounding earthed case. In the Braun electrostatic voltmeter, this is put to practical use for measuring voltages of the order of a few thousand. In this instrument, a movable metal strip *AB*, Fig. 2.4., pivoted at *O*, is in electrical contact with the insulated metal rod *CD*. The surrounding case is grounded. When *CD* is joined to a conductor charged to high potential (for example, to one knob of a Wimshurst electrostatic machine, whose other knob is grounded), the movable rod is deflected an amount which is greater, the higher the potential.

2.10. Current through a High Resistance. The student will recall that when a direct current of *I* amperes flows in a resistance of *R* ohms, the potential difference between the ends of the wire is *IR* volts. For example, if a milliammeter indicates a current of 10 ma in a megohm, or 1,000,000 ohm, resistance, the potential difference across it is $1{,}000{,}000 \times 0{\cdot}010$, or 10,000 volts. Given a sufficiently high resistance, therefore, it is possible to measure voltages of the order of those used in X-ray work, provided a suitable instrument is available for observing the (small) current through the resistance when the high voltage is applied across it.

F. D. Owen-King has described in the British Journal of Radiology another method of utilizing a high resistance to measure the voltage across an X-ray tube when operated with constant potential outfits. This method, which it is stated, measures 250,000 volts with an accuracy of 2 per cent, consists in measuring the voltage across a very small portion *CB*, Fig. 2.5, of the high resistance *AB* through which a small current flows as a result of the application of the tube voltage. The potential difference between *A* and *B* is then as many times greater than that recorded by the voltmeter attached to *B* and *C* as the resistance of *AB* is greater than that of *CB*. For the satisfactory operation of this arrangement, certain special constant " Carbo " resistances were utilized. These are " of specially prepared resistance material immersed in oil and

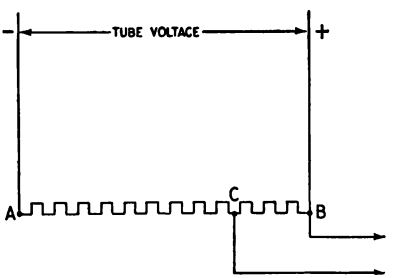


FIG. 2.5. By measurement of the voltage across *BC* a small portion of the very high resistance *AB* in parallel with an X-ray tube the potential difference across the tube may be measured.

contained in porcelain tubes, the oil serving the purpose of cooling the resistance units and preventing corona effects ".

Further details concerning this method will be found in section 13.4, and in Fig. 13.3, p. 251, the reader will find an actual photograph of a high resistance used for the measurement of high voltages.

2.11. The Seeman Spectrograph. This instrument provides an accurate means of measuring the maximum potential difference across a tube from observation of the spectrum of the X-rays emitted by the tube. An explanation of the principle involved must be postponed until we are dealing with the nature of X-rays (see section 8.4).

2.12. Control of Tube Voltage by Rheostat. With the standard transformer arrangement, the voltage across an X-ray tube may be altered and controlled by two means: (1) the rheostat, and (2) the auto-transformer.

In the rheostat use is made of the familiar *IR* drop in voltage due to resistance (see section 2.8 again). Suppose the circuit which includes the primary of the transformer is arranged as in Fig. 2.6. If, at the main supply terminals, the voltage is 220 a.c., then with this arrangement, the voltage across *CD*, the primary of the high tension transformer, is less than 220 by an amount which depends on the resistance of the rheostat and the current. By decreasing the amount of resistance (if the power taken from the transformer remains constant), the voltage drop in the rheostat becomes less and, therefore, the voltage across the primary greater.

In considering the rheostat method of control of voltage, one or two points should be noted.

(*a*) A great deal of heat is developed in a rheostat, because whenever a current flows against resistance, there is a loss in power equal to I^2R watts.

(*b*) Since the drop in voltage through the rheostat depends on the values of both resistance and current, a change in the current may mean a marked change in tube voltage, even for the same setting of the rheostat. For example, if the tube current is cut off without opening the primary circuit * of the transformer, the supply current in the primary circuit drops to a low value, the *IR* drop in the rheostat becomes much smaller, the voltage across the primary much larger, and, therefore, the e.m.f. in the secondary much greater. This is a disadvantage, because an unduly high voltage may then be applied to the tube.

* As will be seen in Chapter V, this can be done in hot filament tubes simply by opening the filament circuit.

On the other hand, if because of a short circuit in the tube circuit, the current supplied the primary should suddenly rise, the rheostat control has the advantage that automatically the tube voltage will drop.

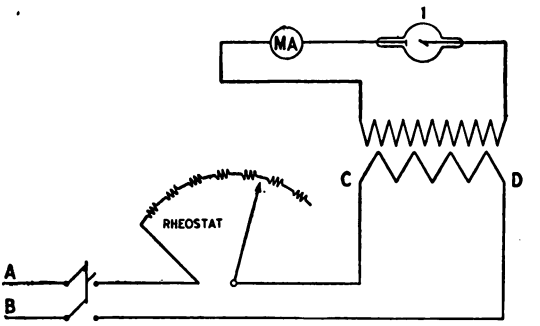


FIG. 2.6. Connections for simple rheostat control of high tension voltage.

In this case, the sudden rise in current greatly increases the *IR* drop in the rheostat and so causes a corresponding decrease in voltage across the primary. The rheostat can then be considered as a kind of safety valve in the case of a short circuit.

2.13. Voltage Control by Auto-transformer. With the type of X-ray tube now in common use, the usual method for controlling tube voltage is by means of an *auto-transformer*. This is essentially a transformer with a single winding whose ends are connected, as shown in Fig. 2.7, to the low voltage a.c. supply mains. From *B*,

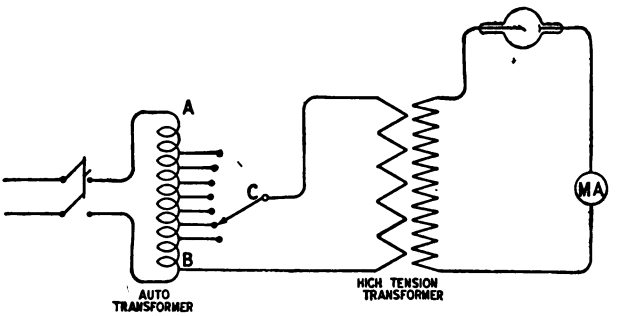


FIG. 2.7. Connections for auto-transformer control of high tension voltage.

one end of the winding and *C* a point whose position may be varied by the use of a number of tappings, wires are led to the primary of the high tension transformer. Because of the principle of electro-magnetic induction, between *B* and *C* a voltage is maintained whose

magnitude is in the same ratio to the supply voltage as the number of turns of the winding between B and C is to the number between A and B. By altering the position of C, voltages ranging from zero to the full supply voltage may be applied to the primary of the high tension transformer, and so a corresponding range of voltages developed in the secondary.

Unlike the rheostat method, auto-transformer control maintains a nearly constant tube voltage even when the tube current varies, because the potential difference between B and C depends on the position of C and is independent of current variations in the supply mains. This has both an advantage and a disadvantage. It is certainly an advantage to have the high tension voltage remain nearly constant in spite of changing loads, because, as we shall see later, the nature of the X-rays emitted by a tube depends on the tube voltage. On the other hand, if a short circuit develops, it is better not to have the high voltage maintained, and in this instance, rheostat control has an advantage over auto-transformer.

2.14. Static Stabilizer. For reasons which will be understood better when X-ray tubes are under discussion, it is frequently desirable to have a constant voltage maintained across the tube. Since in commercial supply lines there are often marked fluctuations in the voltage, special devices called *stabilizers* are often used. These are of such a nature that, in spite of substantial changes in the supply voltage on the input side, there is only a slight change on the output side. A good stabilizer, for example, might show a variation of only 1 per cent on the output side when the input fluctuates as much as 12 per cent.

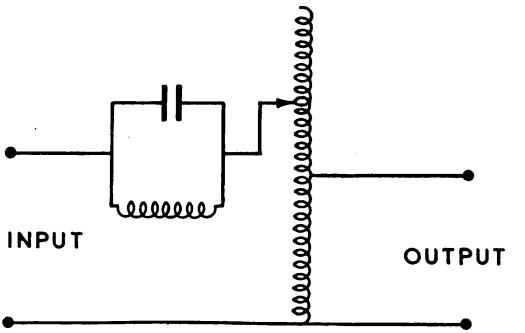
To follow in detail the operation of a stabilizer is not easy, but, if the reader will recall the work on parallel resonance, in section 1.11, and note the following, he can perhaps understand some of the principles involved.*

(*a*) The impedance of a parallel loop with a capacitance C and an inductance L placed as in Fig. 1.10, is a maximum at resonance, that is, when the supply frequency equals the natural frequency.

(*b*) As the voltage V across a choke coil, such as L, Fig. 1.10, rises, the inductance L (the number of linkages per ampere) falls. Hence, in a parallel loop, with a rise in V there is a rise also in its natural frequency, since this equals $\frac{1}{2\pi\sqrt{CL}}$.

* An excellent discussion of basic principles is given in an article by R. S. Wright, *British Journal of Radiology*, p. 339, 1931.

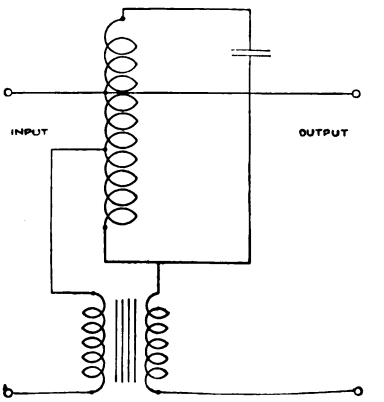
(*c*) Now suppose the capacitance and the inductance of a loop are so adjusted (for a given V) that the natural frequency is less than that of the supply, 40 as against 50, for example. Then, if such a loop is



Courtesy Watson and Sons (Electro-Medical) Ltd.

FIG. 2.8. Simplified diagram of a standard stabilizing unit for a diagnostic transformer set.

placed in a stabilizing unit, as in Fig. 2.8, *when the supply V rises, L* falls, the frequency rises towards resonance and *the impedance increases.* Hence the supply current tends to remain constant. Conversely, if V falls, the impedance drops, with the same result.



Courtesy General X-ray Corporation

FIG. 2.9. To illustrate the principle of a constant voltage stabilizer. For a 12 per cent variation in voltage on the input side, the output voltage varies only 1 per cent.

The diagram in Fig. 2.9, given the author by Mr. W. C. Baldwin of the U.S. General Electric Company, gives an idea of the construc-

tion of a practical stabilizer. Figure 2.8 is a simplified drawing of a stabilizing unit used in a diagnostic set, given the author by Watson & Sons (Electro-Medical) Ltd, London.

PROBLEMS AND QUESTIONS

1. What information should be given about the output of a transformer for X-ray work?

2. In a step-up transformer, the secondary has 1,000 times as many turns as the primary. When 10 ma are delivered at 100,000 volts, what is the current in the primary circuit? (Assume the transformer 100 per cent efficient.)

3. Describe, with simple diagrams, the two chief ways of controlling the voltage applied to an X-ray tube.

4. Make diagrams illustrating the control of voltage applied to an X-ray tube, (i) by rheostat, (ii) by auto-transformer. Explain also why the rheostat acts as a kind of safety valve when a " short " develops in the tube circuit.

5. How is the voltage across an X-ray tube measured? Describe several means.

6. Explain (i) why a voltmeter across the primary of an X-ray transformer can be (and often is) marked to read secondary kilovolts ; (ii) the objection to this practice.

7. Explain fully the meaning of the following portion of the table placed over the control board of an X-ray transformer.

Primary Voltage	Auto-transformer Button	Tube Voltage	
		10 ma	30 ma
80	3	77 kv	72 kv
90	8	88 kv	83 kv

Hence point out the objection to a prereading kilovoltmeter.

8. Describe two ways in which a very high resistance can be used to measure the p.d. across an X-ray tube.

9. A certain transformer has 230 turns on the primary and 100,000 turns on the secondary. If the regulation for a secondary current of 400 ma is 10 per cent, find the voltage between the secondary terminals when this current is being delivered, if the supply is 230 volts a.c. *Ans.* 90 kVp.

10. Calculate approximately the current taken from 200 volt a.c. mains when the secondary of a transformer, assumed 100 per cent efficient, delivers 150 ma at 100 kV peak. *Ans.* 52·5 amps.

11. A 10 : 1 ratio step-down transformer, assumed to have no losses, has its secondary winding connected in series with a resistance of 4 ohms and an inductance of $\frac{3}{1000\pi}$ henry. If the primary is joined to 200 volt, 50 cycles per second a.c. supply terminals, find : (*a*) the secondary current, (*b*) the primary current. *Ans.* (*a*) 4 amps ; (*b*) 0·4 amp.

12. The primary winding of a 1,000 : 1 ratio high tension transformer has negligible resistance and is connected in series with a variable control resistance. When this resistance is set at 20 ohms, a current of 1 ampere is taken from 200 volt, 50 cycle per second a.c. mains, the secondary circuit being open. Assuming that the transformer losses are negligible, find the open-circuit voltage across the secondary terminals. *Ans.* 180,000 volts.

13. A high tension transformer supplies an X-ray tube with a current of 200 ma at 70 kVp when it is connected to 200 volt a.c. supply terminals. If the total resistance of the cables connecting the transformer to the mains is 0·2 ohm, find approximately the voltage drop along the cables. *Ans.* 9·9 volts. (A more accurate solution gives 10·4 volts.)

14. Assuming the answer to problem 13 is 10·0 volts, and that the transformer ratio is 300 : 1, find the inherent regulation for a load of 200 ma at 70 kVp. *Ans.* 12·2 per cent.

15. Why should an auto-transformer be set at a higher button when the tube current is increased, if one wishes to maintain the same potential difference across the X-ray tube?

N.B.—For additional transformer problems, see the end of Chapter VI.

CHAPTER III

CATHODE RAYS

IN the original type of X-ray tube a current passes through a rarefied gas ; in the hot filament tube a current passes, although the vacuum may be nearly as perfect as modern means of exhaustion can make it. Before the action of either can be understood, it is necessary to consider somewhat in detail the whole question of the passage of electricity through a gas.

3.1. Conductivity of Air. Suppose an electroscope, made with the most perfect insulation possible, is given a charge. If the deflection of the leaf is observed hour after hour it will be found that, although there is an extremely slight falling of the leaf, the charge is retained even for days. We conclude, therefore, that while air is not a *perfect* insulator, at any rate it is an extremely poor conductor of electricity. (Evidence that air is not a perfect insulator has been given implicitly when it was pointed out that, once the voltage across two conductors exceeds a certain value, a spark jumps the gap between them.)

It is possible, however, to put air into a fairly good conducting state. A simple experiment will illustrate one means of doing so. Suppose a lighted match is held near the projecting end of a charged electroscope. It will be found that in a few seconds the leaf has fallen and the electroscope is discharged. The air in the neighbourhood of the electroscope has had its conductivity enormously increased by the presence of the flame. In other words, the flame is what we call an *ionizing agent*, causing marked ionization of the air in its neighbourhood.

Suppose we have an arrangement of apparatus similar to that illustrated in Fig. 3.1. In this case air from the neighbourhood of a flame may be sucked through a tube LM, into which projects the top K of the insulated rod of a charged electroscope. With such an arrangement it will be found that as soon as the air from the flame is sucked along the pipe the electroscope begins to lose its charge. Evidently air in the conducting state can be carried from place to place.

Imagine next, that the apparatus is altered so that the ionized air in its passage along the tube has to pass between two plates P_1 and

P_2, Fig. 3.2, which are joined, one to the positive, the other to the negative terminal of an electrical machine or high voltage battery.

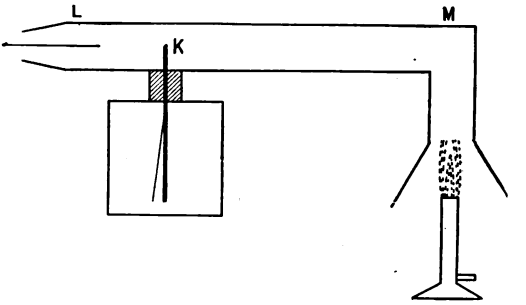


FIG. 3.1. Ions from the neighbourhood of flame when drawn along the tube discharge the electroscope.

It will now be found that, in spite of the suction through the tube, the electroscope *retains* its charge. In other words, the conducting air, after passing between the charged plates has lost its conductivity or is no longer ionized.

The removal of the conductivity by the charged plates (and many other experiments) proves that air is made a conductor because of the formation by the flame of small *electrified* particles. These particles, which we shall see presently may be either positive or negative, are called *ions*. Their existence provides a ready explana-

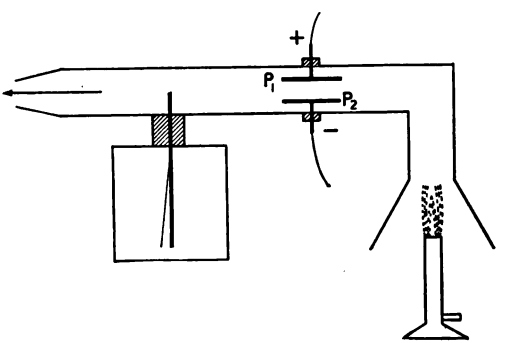


FIG. 3.2. Ions drawn along the tube are removed by an electric field across the plates P_1 and P_2.

tion of the discharge of the electroscope. If it is positively charged and ions are found near it, positive ions will be repelled, negative attracted. Each negative ion on reaching the insulated rod of the electroscope will annul some of the positive charge on it until finally

the electroscope is completely discharged. Moreover, all the time the discharge is taking place *there is a stream of positive ions in one direction, negative in the opposite.* Such a stream of ions constitutes an electric current through the air.

3.2. Conductivity of Air at Reduced Pressure. Before explaining just what the nature of ions is, reference must be made to experiments relating to the conductivity of air at pressures considerably less than atmospheric. Suppose that the terminals of a "vacuum"

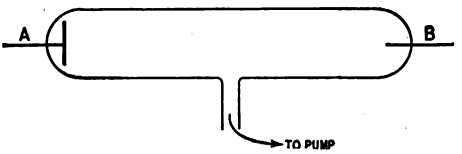


FIG. 3.3. A simple vacuum tube with internal electrodes.

tube with electrodes *A* and *B*, Fig. 3.3, are joined to an induction coil, and that the tube at the start contains atmospheric air, with the electrodes at such a distance apart that no spark discharge can take place. If, now, by means of an exhaust pump, the air is gradually removed from the tube, a stage is soon reached at which a discharge passes readily, this stage being indicated by a line of luminosity which extends from one electrode to the other. As exhaustion proceeds the current passes more and more readily until a second stage is reached beyond which the current passes less readily, until finally, when a very high vacuum has been attained, the resistance is so great that the tube will not conduct at all. Some actual measurements (taken from Townsend's *Electricity in Gases*) are given in Table III. This table

TABLE III

Pressure	4 mm	2·84	1·65	1·04	0·66	0·4	0·29	0·24	0·17
Voltage	650 volts	620	500	470	490	530	590	630	740

gives the voltages necessary to maintain a current of 10 ma through a tube 3 cm in diameter, with electrodes 11·5 cm apart, at various pressures.* It will easily be seen that as the pressure lowers, at first

* Readers will recall that the pressure of a gas is frequently expressed in terms of the length of the column of mercury it will support. Atmospheric air, for example, will support a column of mercury whose height varies from day to day, but is in the neighbourhood of 760 mm. In the experiment to which Table III has reference, an air pressure has been reached which supports a column of mercury only 17/100 mm high.

a lower and lower voltage is required, but after a certain critical value has been reached, higher and higher voltages are necessary. Evidently, then, *the resistance of a vacuum tube (or a gas X-ray tube) depends on the degree to which it has been exhausted.* Moreover, after a certain critical pressure has been passed, it is more and more difficult to pass a given current through an exhausted tube. Technically, it is said that the tube becomes *harder*, as the pressure gets lower. The harder a gas X-ray tube is, therefore, the greater the voltage necessary to maintain a given current through it. Conversely, the tube is said to be " soft " when the gas is in a fairly good conducting state.

3.3. Appearance of Vacuum Tube. The appearance of a vacuum tube when conducting a current at low pressures is very beautiful, and has certain general characteristics which it is well to note. Initially, or very shortly after the gas has become conducting, a single sharp narrow streamer extends the length of the tube. As the pressure is reduced the band of light becomes wider and more and more diffuse until the whole tube is filled with luminosity. At

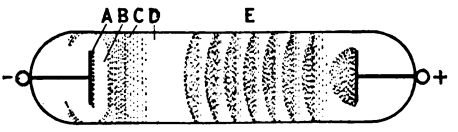


FIG. 3.4. Appearance of a vacuum tube carrying a discharge at a pressure in the neighbourhood of one half a millimetre of mercury.

still lower pressures (of the order of half a millimetre) the tube has a striking and very characteristic appearance. (1) Around the cathode is a thin luminous layer, *A* in Fig. 3.4 ; (2) next is a sharply defined dark space *B*, followed by, (3) another luminous region *C*, then (4) a second ill-defined dark region *D*, and finally (5) a column of luminosity *E*, extending to the anode. At certain pressures this column is broken up into beautiful striations, that is, narrow regions alternately dark and light.

Most important of these regions is the sharply defined dark space, the Crookes' dark space, as it is called, or sometimes " the " dark space. With decreasing pressure, its width continues to increase, and is indeed a rough measure of the degree to which the tube has been exhausted. In the case of a gas X-ray tube, the dark space should fill the whole tube. If, by any chance, an X-ray tube presents the above appearance, that is, one with marked luminosity, the

pressure is much too high and the tube must be re-exhausted before it is of any use. In the case of a hot filament tube, careless manipulation may result in the liberation of gas. If sufficient gas is present, this will be evident by the general luminosity filling the tube when a high voltage is applied. Again, re-exhaustion is the only remedy.

3.4. Properties of Cathode Rays. When exhaustion is extended beyond that giving rise to the above characteristic appearance, the dark space, as already noted, grows wider and wider until it finally fills practically the whole tube. This occurs when the pressure has now been reduced * to about 1/100 mm, a value which is of the order of that in a gas X-ray tube. At this pressure a very faint beam of light proceeding *at right angles* to the cathode is frequently visible. Depending on conditions, this beam may be narrow, covering only a small portion of the face of the cathode, or it may cover nearly the whole of it; it may be extremely faint, or it may be well defined. (Often it is quite visible in a " soft " X-ray bulb.) The direction of this beam, moreover, is independent of the position of the anode. For example, in a tube of the shape illustrated in Fig. 3.5. the beam is still at right angles to the cathode, although the anode is in an arm at one side of the tube.

A second important appearance is characteristic of this stage. The walls of the tube, particularly at the end opposite the cathode, are seen to fluoresce with a glow, frequently greenish, whose colour, however, depends on the composition of the glass. That the fluorescent light has some connection with the faint streamers is readily shown by simply bringing one pole of a magnet near the cathode end of the tube. Both the faint beam of light and the position of the fluorescent light at the other end move simultaneously.

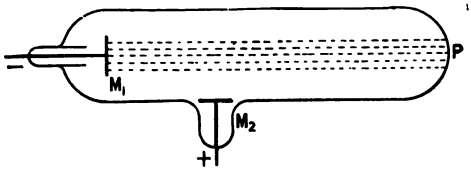


FIG. 3.5. Cathode rays leave the cathode normally.

The name *cathode rays* has been given to the faint beam of light. What is their nature? Before answering this question it is desirable to look at some properties of the rays. From what has just been stated, cathode rays (1) are deflected from their path by a magnetic field, and (2) excite fluorescence where they strike the walls of a glass tube. (3) They travel in straight lines when no deflecting electric or magnetic fields are present. This is readily shown by using a tube

* We speak of raising the vacuum when we lower the pressure.

of the kind illustrated in Fig. 3.6. With such a tube it is observed that if an obstacle P is placed in the path of the rays, a *sharp* shadow is cast on the end of the tube, all the region around the shadow

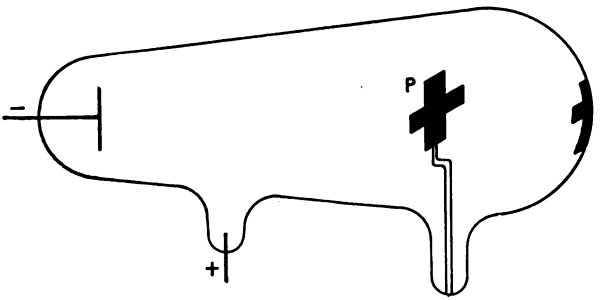


FIG. 3.6. A sharp shadow of the cross P is cast by a beam of cathode rays.

strongly fluorescing. This could be caused only by a beam which, like light rays, travels in straight lines. (4) Cathode rays represent a considerable amount of kinetic energy. This may be shown by using, not a plane cathode, as represented in Fig. 3.5, but a concave one. By this means the beam of rays (which, it was pointed out above, proceed normally from the cathode) can be brought to a focus at a point, as illustrated in Fig. 3.7. If, now, a thin piece of metal be placed in a tube so that the spot to which the rays are focused is on the surface of the metal, in a short time incandescence will be observed in the neighbourhood of the spot. On impact of the rays against the metal a large amount of heat is developed. (This point is of very great importance in connection with the action of either the

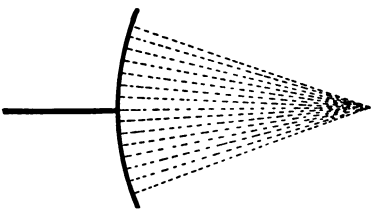


FIG. 3.7. Focusing of cathode rays.

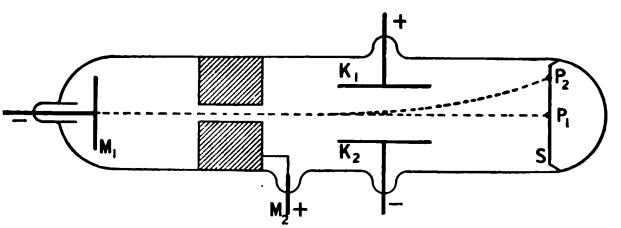


FIG. 3.8. Cathode rays are deflected by the electric field between the plates K_1 and K_2.

gas or the hot filament tube. (5) Cathode rays are deflected from their path by an *electric* as well as by a magnetic field. To show this a tube constructed as represented in Fig. 3.8 is used. By having a small cylindrical opening in the centre of the anode, a narrow pencil of cathode rays may be obtained. This beam may be visible for only a short distance from the cathode, if indeed it can be seen at all, but, if at the far end of the tube, a fluorescent screen S be placed, the presence of the rays is at once evident by a round fluorescent spot at P_1 on the screen. Suppose, now, the tube has been constructed with two metal plates K_1 and K_2 and that these are joined, one to the positive, the other to the negative terminal of a battery. It will then be found that the spot of light shifts from P_1 to P_2. *In their passage through the electric field between the plates, the rays have been deflected.*

From this and the other properties enumerated, we conclude that cathode rays consist of *a stream of electrified particles*. Moreover, from the direction of the deflection by the electric field, the charge they carry is at once seen to be *negative*.

3.5. Nature of Cathode Rays. The experiments which led to the discovery of these properties of cathode rays left no doubt about their corpuscular and electrical nature. Moreover, they provided the answer to questions which naturally arise concerning the size of the particles, their speed, and the magnitude of the charge they carry. A glance at Fig. 3.8 will show that it is a simple matter to measure on the screen S the distance from P_1 to P_2, that is, to measure the amount the beam is deflected ; and it should not be difficult to see that this

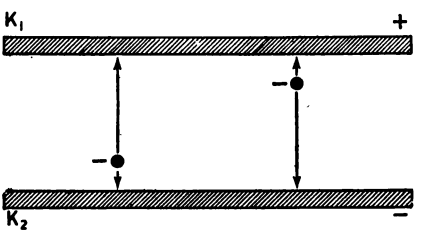


FIG. 3.9. The principle of Millikan's oil drop experiment. A drop, represented by the black dot, is pulled downwards by the force of gravity, upwards by the electric field between the plates K_1 and K_2.

depends on the very things we wish to know. To begin with, the greater the electric charge the particle has and the larger the voltage across the plates K_1 and K_2, the greater the force pushing the particle to one side. But heavy particles are not pushed aside as readily as light, nor fast particles as easily as slow, hence the amount of deflec-

tion depends not only on the force acting on a particle but also on its mass and its speed. For the trained physicist comparatively simple calculations connect all these factors together, and from his calculations and observations, made with both electric and magnetic fields, it can be shown that the value of $\frac{e}{m}$, that is, the ratio of the charge carried by a cathode ray to its mass, is equal to $1{\cdot}76 \times 10^8$ coulombs per gram.

As researches concerning the conduction of electricity through gases continued, it became evident that the charge carried by a cathode ray was a fundamental unit of electricity. It would be out of place in this book to refer in detail to the pioneer investigations establishing this fact, and a brief reference is made to but one outstanding investigation, the famous oil drop experiment performed by Millikan. Like a few other famous experiments it is beautiful in its simplicity. By means of an atomizer, oil drops are sprayed in the space between two charged plates; and the drops are then given a charge by ionizing the air in this region. A single drop ordinarily will fall slowly due to its weight, but, if it has a negative charge and the positive plate is above it, as in Fig. 3.9, the electric force acting on the drop will be in an upward direction, and may easily be adjusted until it exactly balances the downward pull of the earth. The drop will then be balanced in space, somewhat like Mahomet's coffin. Calculations based on this experiment enable the exact charge on the drop to be obtained and show that the charge is always equal to that on a cathode ray or to some multiple of it. Smaller amounts have never been observed, and larger amounts occur in exact multiples of this fundamental unit of charge. The actual magnitude of the fundamental or electrical unit is $4{\cdot}80 \times 10^{-10}$ statcoulombs,* or $1{\cdot}60 \times 10^{-19}$ coulombs.*

From work in electrolysis we know that 96,490 coulombs is the charge carried by the ions contained in 1·008 gm of hydrogen, or

$$\frac{\text{charge on a hydrogen ion}}{\text{mass of a hydrogen ion}} = \frac{96{,}490}{1{\cdot}008} \text{ coulombs per gram,}$$

or

$$\frac{e'}{M} = 9{\cdot}55 \times 10^4 \text{ coulombs per gram,}$$

* It will be recalled that 1 statcoulomb is such a quantity of electricity that when placed 1 cm away from a similar quantity, with air as the medium between them, the force of repulsion between the charges is 1 dyne. It will be useful to remember, particularly when we discuss the question of X-ray dosage, that

1 coulomb or 1 ampere-second $= 3 \times 10^9$ statcoulombs.

where e' represents the charge on a hydrogen ion and M its mass. Since experiment shows that e, the charge on a cathode ray, is equal to e', the charge on a hydrogen ion, it follows that M the mass of a hydrogen atom is about $\frac{1{\cdot}76 \times 10^8}{9{\cdot}55 \times 10^4}$ or about 1,840 times greater than m the mass of a cathode ray.* In passing we may note that the mass of a hydrogen atom is $1{\cdot}66 \times 10^{-24}$ gm, that of a slow cathode ray $9{\cdot}09 \times 10^{-28}$ gm.

In cathode rays, then, we have to deal with particles of this small mass, all carrying the same negative charge of electricity. It is important to realize that the mass of a cathode ray is the same regardless of the nature of the materials in the cathode ray tube. The cathode may be made of iron, or of copper, or of silver, or of aluminium, or any other metallic substance; the gas in the tube before it was evacuated may have been ordinary air, or oxygen, or hydrogen, or carbon dioxide, or any other kind—in all cases the same result is obtained. All slow cathode rays have this same mass. This was a startling discovery because it proved that there was a common constituent to all kinds of matter. The atom can no longer be considered uncut or uncuttable as it was throughout most of the nineteenth century. It must contain particles with a mass nearly two thousand times less than that of the hydrogen atom.

The speed of cathode rays depends on the potential difference between the cathode and the anode in the same way as the speed of a falling body depends on the height from which it has fallen, and may be thousands of miles per second. For example, for a potential difference of 10,000 volts, the speed is about 37,000 miles per second, or about one fifth of the velocity of light; for 100,000 volts, the speed is over 100,000 miles per second; and for a million volts, ninety-five per cent of the speed of light is obtained.

It is instructive to calculate the speed of a cathode ray for a given voltage. To do so the student must recall that unit potential difference exists between two points or two conductors, when unit amount of work is done in taking a unit charge from one point to the other, or when unit amount of energy is gained if the unit charge falls under unit potential difference. To be more specific, if unit potential difference, which for convenience we shall call 1 statvolt, exists between two conductors, and 1 statcoulomb falls through this potential

* This is true only when the speed of the cathode rays is not great. Actually the mass is a function of the velocity, and at extremely high speeds the increase in mass becomes of great importance.

difference, the energy gained is 1 erg, the fundamental unit of energy. Another important energy unit in common use is the *electron-volt*. This is the amount of energy acquired when a particle having a charge equal to the fundamental or electronic unit falls through a potential difference of 1 volt.

It follows at once that, if the potential difference is V statvolts, and the charge is e statcoulombs, the energy gained is Ve ergs. Since the usual unit of potential difference is the volt, the student should remember that 300 volts = 1 statvolt; or that to change from volts to statvolts, you must divide by 300.

Suppose, now, that a cathode ray (with charge $4{\cdot}80 \times 10^{-10}$ statcoulombs) falls through 10,000 volts. The energy * it acquires

$$= \frac{10{,}000}{300} \times 4{\cdot}8 \times 10^{-10} \text{ ergs},$$

$$= 1{\cdot}6 \times 10^{-8} \text{ ergs.}*$$

This energy appears as kinetic. Now the kinetic energy of a particle of mass m grams moving with velocity v cm per sec. is $\frac{1}{2}mv^2$ ergs. In the case of the cathode ray we have seen that

$$m = 9{\cdot}09 \times 10^{-28} \text{ gm.}$$

Therefore, the kinetic energy of the particle

$$= \tfrac{1}{2} \times 9{\cdot}09 \times 10^{-28} \times v^2 \text{ ergs.}$$

Hence,

$$\tfrac{1}{2} \times 9{\cdot}0 \times 10^{-28} \times v^2 = 1{\cdot}6 \times 10^{-8},$$

from which

$$v = 59{\cdot}6 \times 10^8 \text{ cm per second}$$
$$= 37{,}100 \text{ miles per second.}$$

3.6. Structure of the Atom. As we have just seen, the discovery of cathode rays showed that atoms of all elements must contain negatively charged particles, a conclusion which was amply confirmed by subsequent work. These particles we now call *electrons*, reserving the name cathode rays for electrons which are shot down evacuated tubes of the kind shown in Figs. 3.5 and 3.6. Electrons may be released from atoms in a number of different ways. A very common method which we shall discuss more fully in Chapter V consists in heating a metal to incandescence, in which case electrons evaporate from the metal, or, to be more scientific, there is a *thermionic emission* of electrons. In a radio tube, for example, the filament which you sometimes can see glowing, is heated to obtain a supply of electrons.

* This amount of energy is more often described as 10,000 electron-volts.

If, therefore, an evacuated tube is made like the one shown in Fig. 3.10, where the cathode of Fig. 3.5 is replaced by a wire *F heated to incandescence by passing an electric current through it, a beam of

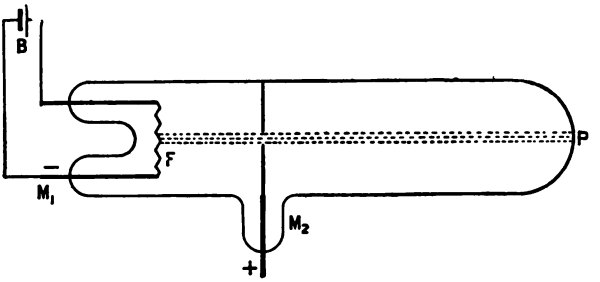


FIG. 3.10. A simple electron gun. Electrons are liberated from the heated filament F.

cathode rays is shot down the tube when the filamant is joined to the negative terminal and the anode to the positive terminal of an induction coil or any other source of direct voltage. Such an arrangement constitutes the essential features of what is sometimes called an *electron gun.*

The new atom which contains electrons must have a structure far from simple. Since an atom as a whole exhibits no electrical charge it must contain enough positive electricity to neutralize the negative on the electrons. What does it look like, and where is the positive electricity? Can we form a mental picture of it? The answer to these questions has not always been the same, but for a number of years it has been possible to visualize a model atom which has been extremely fruitful in explaining and interpreting many facts. This atom consists of a positively charged centre or *nucleus* accounting for almost the whole of its mass, together with a number of electrons *whose total negative charge exactly equals the positive charge on the nucleus.* So small are both nucleus and electron that if an atom were enlarged to be the size of a balloon 60 feet in diameter, the nucleus and each electron would not be much bigger than a grain of sand. On this view the atom is a miniature solar system with the electrons revolving about the nucleus much as the planets revolve about the sun.

To distinguish one atom from another, two quantities must be known : (1) the *atomic weight* or the number proportional to the mass of the atom ; (2) the *atomic number.* One or two concrete examples

* Frequently the wire is coated with a material like lime or calcium oxide which liberates electrons copiously when the wire is heated at a lower temperature than is necessary for the uncoated wire.

should make clear the meaning of atomic number. There is overwhelming evidence that in the atom of hydrogen, the lightest element, there is but one electron, with its unit negative charge, moving about the nucleus with an equivalent positive charge; in helium, the next lightest element, there are two electrons and the nucleus has two units of positive electricity; in lithium, the third lightest, there are three electrons and three positive unit charges on the nucleus; and, to give one other example, in the mercury atom, there are eighty electrons and the nucleus has eighty units of positive electricity. The atomic number is just the number of unit positive charges carried by the nucleus—which, of course, is the same thing as the number of electrons in the normal atom. Hydrogen, then, has an atomic number of 1, lithium of 2, helium of 3, and mercury of 80. In modern physics the atomic number is of even greater importance than the atomic weight because the chemical properties of an element depend on the number and arrangement of the electrons surrounding the nucleus, and this depends on the atomic number.

3.7. Meaning of Ionization. Since negative electricity attracts positive, each electron is strongly attracted by the nucleus. This electrostatic attraction provides the centripetal force necessary to keep the electron in orbital motion about the nucleus. If it were not for its motion, the electron would "fall into" the nucleus. By exerting a pull outwards, however, it is possible to remove an electron completely out of the atom away from the attraction of the nucleus. When that has been done, the nucleus has one unit of positive electricity in excess of the amount necessary to neutralize the negative charge on the remaining electrons, and we have what is called a positive atom-ion, or more often, just a *positive ion*. Sometimes two electrons are removed from the atom, and we then have a doubly charged positive ion. The atom in each case is said to be *ionized*, and the means by which the electron or electrons have been removed are called ionizing agents. X-rays, gamma rays from radium, and, as we have already seen, flames are examples of such agents. The electron which has been removed from an atom does not always remain in solitary state, but frequently attracts to itself a neutral molecule or atom, or possibly several of them, forming a negative ion.

On this view electricity is never created, but is of the very essence of matter. When an ebonite rod is rubbed on wool, little forces (which we do not understand any too well) are brought into play which cause electrons to pass from the wool to the rod. For every

million electrons gained by the rod, the wool loses a million. Consequently, whenever the rod acquires a million units of negative electricity, the wool, having a million positive units unbalanced by the electrons it has lost, acquires an equal positive charge.

A battery or a dynamo is not a means of creating electricity, but a device which separates positive from negative, with a resulting potential difference between its terminals. When a current flows in a circuit, it is simply a movement of electrical charges—sometimes electrons only ; sometimes negative ions in one direction, positive in the opposite.

3.8. Ionization by Collision. The ability to ionize a gas or a vapour through which it is passing is an important property of a rapidly moving electron. If moving quickly enough, an electron may pass right through an atom leaving it unharmed ; if moving very slowly, the electron may not have enough energy to do any damage ; but over a wide range of speeds, it will remove electrons from many of the atoms which lie in its path. As we have seen, whenever an atom loses an electron it becomes a positive ion. Hence the path of a fast electron is marked by a trail of ions.* This production of ions by a moving particle is one of the commonest ways of making a gas conducting. In the next two chapters we shall study this method of ionization in greater detail.

3.9. Electron Bombardment. Attention has already been directed to the fact that intense heat may be developed when electrons are suddenly stopped by a target. It is not surprising, therefore, that important effects may be brought about by controlled bombardment of certain materials by electrons or cathode rays.

Special electron tubes have been constructed for the specific purpose of obtaining homogeneous beams of electrons with speeds corresponding to potential drops over voltages ranging from 1 to 15 kilovolts in the case of one tube, or from 10 to 100 kilovolts in another. Such tubes are convenient for a study of the effects of the electron bombardment of biological material.

Much faster electrons have been utilized in certain bombarding experiments, in which the cathode rays, after passing right through a thin sheet of metal in the wall of the cathode ray tube, emerge into the outside air. Tubes of this kind are sometimes called Lenard-Coolidge, in honour of Lenard, a German physicist, and Coolidge, of the General Electric Research Laboratory at Schenectady, N.Y. Lenard, in the last decade of the nineteenth century, made pioneer

* See section 10.5.

investigations relating to the passage of cathode rays through metallic foil. Coolidge followed up his work using potential differences exceeding a million volts to speed up the rays. Coolidge and other workers have shown that, under the action of these cathode rays outside the tube, yeast, ergosterol, and a few other substances produce vitamin D; that new species may be originated in plants and in animals; that changes in colour may be brought about in glass and other substances; and that it is possible to distinguish natural from artificial sapphire by the difference in their response to the rays.

In instruments such as the *betratron* and the *synchrotron*, to which reference is made in Chapter XIII, electrons are accelerated until they acquire speeds the equivalent of potential drops of many million volts. Investigations are being carried out to examine the biological effect of such very high speed electrons.

3.10. Origin of Roentgen Rays. For the radiologist probably the most important use of cathode rays is to generate roentgen or X-rays. When cathode rays or high speed electrons are suddenly stopped by impinging against a hard metal target, the spot struck by the beam is the source of the invisible light called X-rays. Details concerning tubes used for this purpose, as well as concerning the properties of such tubes will be given in Chapter V.

3.11. The Oscilloscope. One of the most useful tools in a modern physics laboratory is the cathode-ray oscilloscope. This is an instrument in which the movement of a small cathode-ray spot on a fluorescent screen provides valuable visual information about many different kinds of phenomena. Although the oscilloscope has a number of external controls and internally has a variety of electrical circuits, basically it is just an application of the principles utilized in the apparatus shown in Fig. 3.8 and Fig. 3.10.

Electrons from an electron gun are focused by means of an electrostatic lens or a similar device to form a narrow beam which gives rise to a small spot when it hits a fluorescent screen at the observer end of the oscilloscope. The beam on its way to the screen passes between two pairs of deflecting plates so arranged that when a potential difference is applied to one pair, the electron beam, and so the spot on the screen, is deflected horizontally along an x-axis, but, when applied to the other pair, the deflection is vertical along a y-axis. If the voltage applied to either pair has a constant value, a corresponding constant deflection of the spot is obtained.

Now suppose that, with no potential difference across the y-pair of plates, a periodic voltage is applied to the x-pair. In that case the

spot of light moves back and forth along the x-axis on either side of its undeflected position, the observer seeing (unless the frequency is extremely low) a line of fluorescent light. In the standard type of oscilloscope what is called a *sweep circuit* makes it possible to apply to the x-plates a special kind of periodic voltage, namely one which gradually rises to a maximum (whose magnitude may be varied) and then, almost instantaneously, drops to zero. In this case the observer still sees a line of fluorescent light, but he must now think of the spot moving across the screen and then jumping back to the starting point, the whole process being repeated regularly. The time of sweep may be varied over wide limits, the range of values varying with the instrument. For example, in one oscilloscope the time of sweep ranges from 0·2 seconds to 6 microseconds; in another from 20 milliseconds to 10 microseconds; still another has two sweep circuits, one of "low" velocity ranging from 1 second to 10 microseconds, and a fast, with a range from 0·1 seconds to 1 microsecond.

Suppose now that the y-plates are brought into action in ways whose number is almost legion, because the oscilloscope can be used in connection with any arrangement where a potential difference is developed. We note a few examples.

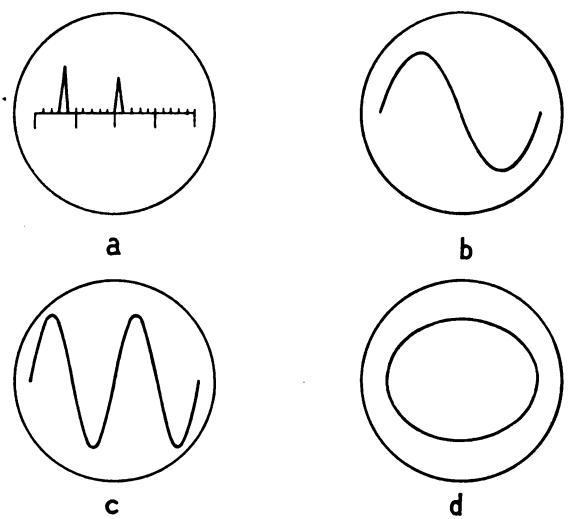


FIG. 3.11. Typical patterns observed on an oscilloscope. (*a*) Pulses due to reflection of radio signals. (*b*) An a.c. cycle, when the frequency of the sweep circuit equals the frequency of the a.c. supply. (*c*) Two cycles, when the sweep frequency is one half that of the supply. (*d*) Pattern obtained without use of sweep showing a phase difference of 90° between the current and the voltage in an a.c. circuit.

In certain investigations pulses of radio waves are sent up to the ionosphere where they are reflected back to the earth. By connecting two points on the receiving circuit to the y-plates, each reflected pulse gives rise to a vertical kick of the cathode-ray spot, somewhat as shown in Fig. 3.11 (*a*), where two pulses are indicated. Moreover, the time interval between the pulses can be read off the time scale which is controlled by the sweep circuit.

As another example, suppose the y-plates are connected to two points on a circuit carrying an ordinary 50 cycles per second a.c. Since the periodic changes in potential difference cause the spot to move to and fro vertically, while at the same time it is carried horizontally by the sweep circuit, a pattern such as Fig. 3.11 (*b*) is traced out. If the frequency of the sweep circuit is adjusted (synchronized) to be exactly 50 sweeps per second, this is the pattern obtained, but if the frequency is 25 sweeps per second, the pattern is like that shown in Fig. 3.11 (*c*).

A third example is in the use of the oscilloscope for the analysis of sound vibrations. When sound waves fall on a microphone, the wave pattern gives rise to corresponding differences in potential between points on the microphone circuit and these may be applied to the y-plates.

Two additional points about oscilloscopes should be noted. (*a*) The amount of deflection, both horizontal and vertical, for the same applied voltage can be controlled and varied by *gain* circuits. (*b*) The x-plates may be used without a sweep circuit. For example, suppose an alternating current is flowing in a circuit containing a non-inductive resistance in series with a choke coil of negligible resistance and that the ends of the resistance are connected to the x-plates, the ends of the choke coil to the y-plates. It is left as an exercise for the student to prove that a pattern similar to that shown in Fig. 3.11 (*d*) will be observed on the screen. (Recall that the voltage across the resistance will be in phase with the current, but that across the choke coil will differ in phase from the current by 90°.)

PROBLEMS AND QUESTIONS

1. Is air at atmospheric pressure a conductor of electricity? Describe several ways in which air may be made conducting.
2. Describe the variations in the conductivity of a tube with electrodes, as the air is gradually removed, the electrodes being connected to high voltage terminals.
3. What are ions, electrons, cathode rays?

4. Describe how the voltage across a tube (originally containing air at atmospheric pressure) varies as the air is gradually exhausted, if the tube is carrying a current.

5. Describe the properties of cathode rays with reference to suitable experiments to illustrate these properties.

6. What is meant by the atomic number of an element?

7. Explain, with the aid of a diagram, a method of generating a narrow beam of cathode rays.

8. If a cathode ray has a charge of $4{\cdot}8 \times 10^{-10}$ statcoulomb, how many (i) electron-volts, (ii) ergs, of kinetic energy does it acquire after falling through a p.d. equal to 1,000,000 volts? *Ans.* (i) 10^6; (ii) $1{\cdot}6 \times 10^{-6}$.

9. Find the magnitude in ergs of an electron-volt. *Ans.* $1{\cdot}6 \times 10^{-12}$.

CHAPTER IV

POSITIVE RAYS AND ISOTOPES

4.1. Nature of Conductivity at Atmospheric Pressure. In section 3.1 it was pointed out that even with the most perfect insulation available, an electroscope slowly loses its charge. It should now be evident that, if a few stray ions are at all times present in ordinary air, a ready explanation of this discharge may be given. As a matter of fact, a large number of investigations, many of them dating back to the beginning of this century, have shown conclusively that there is no doubt about the presence of such ions. If, then, an intense electric field is created between two conductors such as the knobs of a simple electrostatic machine or the secondary terminals of an induction coil, these ions, being charged particles, are acted on by a big force, and very quickly acquire a high velocity. If the field is intense enough, the ions have sufficient kinetic energy to ionize neutral atoms or molecules against which they collide. The ions and released electrons resulting from such collisions in their turn are speeded up by the electric field and very quickly they, too, ionize other atoms and molecules. In this way, once an electric field of sufficient intensity has been reached ionization increases so rapidly that a sudden discharge made evident by the crackling spark, takes place. In the case of corona, the field is intense enough to cause a discharge only within a limited region near the high potential conductor. If an earthed conductor should be brought too near, the corona will of course give way to a spark.

4.2. Conductivity at Reduced Pressure. When even a tolerably high voltage is applied to tubes of the kind illustrated in Figs. 3.3, 3.4 and 3.5 no discharge passes if the contained air is at atmospheric pressure, because the field between the electrodes is not sufficiently intense to enable the stray ions to acquire sufficient energy to ionize the neutral atoms or molecules with which they collide. When a partial vacuum is created, however, as we have already noted in section 3.2, there is a discharge in the tube. Because of the greater distance between individual molecules at the lower pressures, an ion now moves a greater distance without obstruction and so has a chance to acquire more energy before an impact takes place. A pressure is reached when the energy so acquired is sufficient to enable the ion to

ionize on collision and there is a rapid accumulation of ions. A current passes, positive ions moving towards the cathode, negative ions and electrons towards the anode. If a stream of cathode rays is wanted, the vacuum is made so good that the liberated electrons, largely formed in the neighbourhood of the cathode, move the full length of the tube with little obstruction. Figure 4.1 is an attempt to

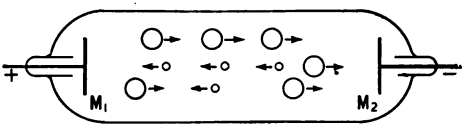


FIG. 4.1. In a tube containing a little gas at not too low a pressure numerous positive and negative ions move in opposite directions.

depict the state of affairs at somewhat higher pressures, when the tube is filled with light, as in an electric neon sign. At this stage there are numerous positive and negative ions.

4.3. Positive Rays. The existence of a stream of positive ions may be shown very beautifully by using a tube in which holes are made in the cathode, not the anode, somewhat as shown in Fig. 4.2. At suitable pressures, in *B*, the portion of the tube beyond the cathode, a narrow beam of light is seen as a continuation of each hole in the cathode, an observation made in 1886 by the German scientist

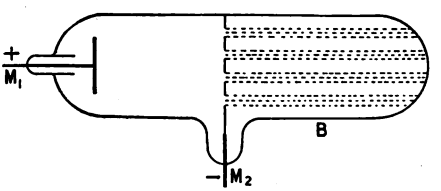


FIG. 4.2. A canal ray tube. Positive ions pass through the perforations in the cathode and, at suitable pressures, give rise to coloured canal ray streamers.

Goldstein. At that date, it must be remembered, neither electrons nor ions had been discovered, and Goldstein, not knowing the true nature of the rays passing through the holes in the cathode, appropriately called them *canal* rays. It remained for another German, Wien, in 1898, to show that canal rays, if made to travel through either an electric or a magnetic field, were deflected to one side, just like cathode rays, and so were electrified particles. There are three very important differences, however, between canal and cathode rays.

(1) The direction of the deflection of canal rays in a tube like the one shown in Fig. 4.3, where a narrow beam passes between the

electrified plates, K_1 and K_2, is *towards* the negative plate, not away from it as in the case of cathode rays. Canal rays, therefore, must be positively charged. This, of course, is just what one should expect, for they are nothing but the stream of positive ions which come up to the cathode and pass through its perforation. In fact, J. J. Thomson, the famous English physicist who was one of the pioneer workers with these rays, changed their name to positive rays.

(2) It is much more difficult to deflect canal rays, stronger electric and magnetic fields being necessary to do so. As a matter of fact, Goldstein tried unsuccessfully to deflect them with a magnetic field. The reason for the difficulty in deflecting the rays is due to the much heavier mass of an ion than that of a cathode ray, because, as we pointed out when dealing with the deflection of cathode rays, the heavier a particle is, the harder it is to push it out of its path.

(3) Measurements of the same kind as are used in cathode-ray deflection tubes show that canal rays are of atomic size, but that their masses are not always the same. If the gas in the discharge tube is changed, the masses of the canal or positive rays are altered also.

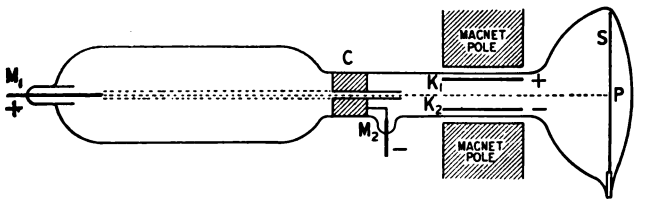
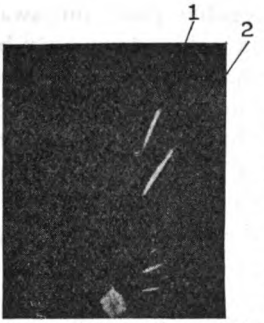


FIG. 4.3. A simple tube for the analysis of a beam of positive rays.

Again this is to be expected once we realize that positive rays originate in the positive ions in the discharge tube. If a tube contains hydrogen, the ionized atoms or molecules of hydrogen will pass through the hole or holes in the cathode; if oxygen, then oxygen atom-ions; and if there is a mixture of these two gases, in the canal ray beam there will be both oxygen and hydrogen ions.

4.4. Chemical Analysis by Positive Rays. If a positive ray beam containing a mixture of ions of different masses passes through an electric and a magnetic field, it will be sorted out into its components. This is the principle of the positive ray method of chemical analysis which was first used by J. J. Thomson with such remarkable consequences that it is necessary to understand it clearly. In the method originally used by Thomson a tube was built somwhat as shown in Fig. 4.3. The rays pass through a fine tunnel in the cathode *C* and



Courtesy Sir J. J. Thomson; the Royal Society and Longmans Green and Co.

FIG. 4.4. Positive Ray Analysis—Early Parabola Method, showing hydrogen atoms and molecules.

on emergence travel across a highly evacuated region until they strike a screen S (or a photographic plate) at the end of the tube. When the screen is coated with certain materials there is a fluorescent spot of light at the place P struck by the rays; or if a photographic plate is used the rays affect it much as light does, and on development an image of the spot is obtained. In Fig. 4.4, an original photograph taken by Thomson, the spot at the lower centre was caused by such a narrow beam of undeflected rays.

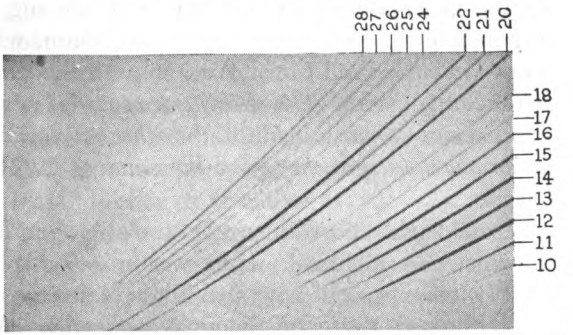
If, however, the beam passes between the electrified plates K_1 and K_2, that is, through an electric field, and at the same time, between the poles of a magnet, there is a sorting out of the rays or ions. When the fields are so arranged that one pushes the particles vertically, the other horizontally, then all particles of the same mass and same electric charge, regardless of their speed, strike the screen or the photographic plate along a curved line. It is much the same as if bullets of different sizes were emitted by a machine gun and on their way to a target were acted on by two forces, one pushing them sideways, the other up or down. With such an arrangement all the bullets of one size would hit the target along one line, of another size along a different line, and so on. If a positive ray beam contains singly charged atoms of hydrogen, of oxygen, and of nitrogen there is a curved line on the plate corresponding to each kind of atom. In Fig. 4.4 the beam which was analyzed in this way has given rise to four or five such curved lines, the line marked 1 arising from singly charged hydrogen atoms, that marked 2 from singly charged hydrogen molecules, which have double the mass since a molecule of hydrogen contains two atoms.

This method of analysis has many advantages. Only an extremely small amount of a substance is necessary to have its presence revealed in this way. The method is even more sensitive than the spectroscope in detecting an element. It may reveal the existence of temporary, unstable groups of atoms which change into something else after the discharge is over. Moreover, on a single photograph a record is left of all the materials which take part in the discharge. A beautiful example of such a record taken by Harmsen, a German scientist, with an improved form of Thomson apparatus and repro-

duced through the kindness of Julius Springer, publisher of *Zeitschrift für Physik*, is shown in Fig. 4.5.

It will be noted that opposite each line on this photograph a number is printed. These numbers give the masses of the corresponding particles on the usual atomic weight scale, and it is hoped that they will emphasize the biggest of all the advantages of positive ray analysis—the accurate comparison of atomic weights. For this purpose the relative displacements of different lines on the plate must be measured. This could be done with fair accuracy on Thomson's original curves, and, indeed, in his hands gave remarkable results, but an improvement in his apparatus was necessary for the exact measurement which modern science demands. Realizing this, Dr. F. W. Aston, originally a collaborator of Thomson, designed new arrangements which gave greater and greater accuracy and led to results of sufficient importance to win for him a Nobel prize. In later years his work, supplemented by that of others, but notably by Bainbridge and by Dempster in the United States, has been one of the most important lines of investigation in experimental physics.

In the forms of apparatus used by the modern experimenters the sorting out of the ions depends, as in the original arrangement, on a suitable combination of electric and magnetic deflecting fields, and



Courtesy Zeitschrift für Physik

FIG. 4.5. Positive Ray Analysis—Later Parabola Method. Note the isotopes of neon mass numbers 20 and 22.

the details of construction need not concern us. In the final photograph, however, we must note one difference. Short straight lines replace the long curves of the Thomson method. A typical photograph is shown in Fig. 4.6.

Students familiar with photographs of optical spectra will note the similarity. Just as a beam containing a mixture of different kinds of

light on passing through a prism is spread out into a spectrum showing all its components, so the beam of positive rays by this method is separated into its constituents. It is not surprising that the apparatus

Courtesy Dr. A. J. Dempster

FIG. 4.6. Positive Ray Analysis—Modern Mass Spectrum, showing isotopes of cadmium.

used in the analysis is called a *mass spectrograph*, and the photograph, in which each line corresponds to an ion of a definite mass, a *mass spectrum*. By measuring the separation of the lines along such a spectrum, an accurate comparison of masses and hence of atomic weights, may be made.

4.5. Isotopes. An analysis by Thomson in 1912 of the contents of a discharge tube containing small quantities of the rare gas neon, led to a very important discovery. This gas, it will be recalled, has an atomic weight of 20·2. Now on his plates Thomson obtained not only a curve corresponding to an atomic weight of 20, but also one corresponding to atomic weight 22. Although there was no known element with the latter atomic weight, the evidence suggested that neon was responsible for both lines. In 1919, Aston, who had resumed his work after the First Great War, showed that there was no doubt about this conclusion. *The element neon was a mixture of two groups of atoms, one of atomic weight* 20, *the other of atomic weight* 22, *mixed in such proportions that they gave the value of* 20·2 *determined by chemical means.*

It will be recalled that according to Dalton's Atomic Theory the atoms of an element are identical. Here was unmistakable evidence that an ordinary element might have two kinds of atoms, of different atomic weights, but with the same chemical properties. As a matter of fact it was easy to accept this conclusion because previous investigations had shown that in unstable radioactive elements, the same phenomena occurred. In the field of radioactivity, which will be discussed in Chapter XII, scientists had become familiar with groups of two or more elements whose atoms have the same number of electrons and identical chemical properties, but different masses. Indeed, in 1913 Soddy, one of the pioneer workers in radioactivity, had coined the name *isotope* to designate each member of such a group. The Thomson-Aston discovery was none the less of extreme

importance because it showed that isotopes could exist in ordinary, that is, nonradioactive elements.

With improved forms of mass spectrographs, it soon became evident that isotopes were the rule, not the exception, as a glance at Table XXIX, at the end of the book, will show. In the element tin, for example, whose atomic weight is usually given as 118·7, there are no less than ten isotopes, with masses ranging from 112 to 124. Although these masses are different, *the atomic number, that is, the number of unit positive charges on the nucleus or the number of surrounding electrons in each is exactly the same, namely* 50. Since the chemical properties depend on this extra-nuclear structure the isotopes cannot be separated chemically. Each isotope belongs to the element tin. It is, therefore, not the mass of an atom which tells you its name, but its atomic number. The distinguishing label of tin is its atomic number 50 ; of silver, its atomic number 47 ; of sodium, its atomic number 11 ; of mercury, its atomic number 80 ; and so on. We may even have different elements with atoms of the same mass. For example, the metallic element calcium with atomic number 20 has an isotope of mass number 40, and so has the gaseous element argon, of atomic number 18. Elements with the same mass number but different atomic numbers are called *isobars*. For example, argon, atomic number 18, potassium, atomic number 19, and calcium, atomic number 20, all are isobars of mass number 40.

Meaning of Nuclide. This is a term in general use to designate a particular species of atom. Thus, each of the ten stable isotopes of tin is a different nuclide. Each has the same atomic number, but different mass number. One nuclide differs from another in either atomic number or mass number or of course both.

4.6. Determination of Atomic Weights by Physical Method. If neon has two groups of atoms of mass numbers 20 and 22, what, it may be asked, is the atomic weight of this element? Can this result be reconciled with the atomic weight of 20·2 determined by chemical means? In chemical reactions the groups of isotopic atoms are not separated and the atomic weight determined chemically is an average value based on combining weights. To obtain the same average value from mass spectrograph data we must know the relative amounts of each isotope. This information is readily obtained from the degree of blackening of the mass spectrum lines on the photographic plate, because the larger the number of ions which strike the plate, the blacker or the denser the image. Neon photographs, for example, show that the 20 component is nine times more dense than

the 22. It is just a matter of simple arithmetic to show that the average atomic weight is 20·2.

4.7. Discovery of Deuterium. The mass spectrograph, therefore, has provided a method of obtaining atomic weights *entirely independent of the old-established chemical means.* If both methods are reliable, values obtained by the two methods should agree. In 1929, the agreement was remarkable, the difference between corresponding values being only about 1 part in 10,000. In that year, however, it was shown that oxygen, which hitherto had been considered an element with only one isotope, of mass 16, had isotopes 17 and 18 present in small quantities. This meant that if the whole system of atomic weights is based on the assignment of 16·000 to the main isotope of oxygen, the average atomic weight of oxygen (the value based on all its isotopes) is slightly greater than 16·000; or conversely, if the *chemical determinations* of atomic weights are continued to be given in terms of 16·000 for oxygen, then the values for all other elements should be slightly less than those determined by the mass spectrograph method. The correction to be made is slight, but it was enough to indicate a disagreement between the atomic weights of hydrogen, as determined by the two methods, which was just greater than possible experimental errors. Birge and Menzel, American physicists, suggested that the lack of agreement might be due to an undetected isotope of hydrogen of mass number 2. Urey, Brickwedde, and Murphy, American scientists also, set out to look for such an isotope spectroscopically, and in 1932 announced the discovery of heavy hydrogen or *deuterium* (symbol D) of mass number 2. In a tank of ordinary hydrogen there is only one part of the heavy variety to several thousands of the light, but after the original discovery of deuterium, means were soon found of increasing its concentration, and eventually of completely isolating it.

Of the compounds of deuterium, D_2O or heavy water has been of outstanding importance as will be seen in Chapter XVI. Of great importance also is a third (radioactive) isotope of hydrogen, H_3, called tritium.

4.8. The Proton. We have seen that the sorting out of positive rays has led to a physical method of determining atomic weights, to the discovery of the existence of isotopes in general, and of heavy hydrogen in particular. Of even greater importance for the development of physics is the use of the mass spectrograph for the accurate measurement of the masses of all isotopes, in terms of the number 16·0000 assigned to the main isotope of oxygen. Hitherto we have

been using whole numbers—the so-called *mass numbers* 35 and 37 for chlorine, 1 and 2 for hydrogen, 20, 21 and 22 for neon, 16, 17 and 18 for oxygen—as the values of atomic masses, without any explicit reference to their exact values. Now with the improved modern instruments measurements of the displacement of the isotopic lines on a mass spectrum plate may be made to a high degree of accuracy. The results of such measurements show that in all cases, masses of isotopes are *very nearly* whole numbers. The few values given in Table IV will illustrate the point.

TABLE IV

A FEW EXACT VALUES OF ISOTOPIC MASSES IN TERMS OF OXYGEN 16=16·0000

Element	Mass Number	Mass
Hydrogen	1	1·00812
Deuterium	2	2·01471
Helium	4	4·00390
Lithium	6	6·01697
Lithium	7	7·01822
Beryllium	9	9·01503
Boron	10	10·01677
Boron	11	11·01244
Carbon	12	12·00382
Nitrogen	14	14·00751
Oxygen	16	16·0000
Neon	20	19·99877
Aluminium	27	26·9899
Argon	40	39·97504

With the discovery of the " nearly whole number rule " for all isotopes, it was inevitable that the hydrogen atom, or more accurately, its nucleus called the *proton*, should be considered as an ultimate unit in the building of more complex atoms. At any rate, serious attention was given the theory that the nuclei of all atoms, in some way, are made of protons, with their positive charges, and negatively charged electrons. As we shall see later, this view is no longer held, nuclei now being considered to be composed of protons and neutrons. Because of its importance in later work a brief further reference will now be made to the problem of isotopic separation.

4.9. Separation of Isotopes. In preceding sections we have learned how, by means of the mass spectrograph, the various isotopes of an element may be separated and their mass numbers evaluated.

There remains the practical problem of so separating the isotopes that usable amounts of each variety can be collected. .

During World War II this problem was of great importance in the years preceding the successful attempts to utilize nuclear energy arising from the fission of the element uranium, a question which will be considered in Chapter XVI. Natural uranium has three isotopes, one of mass number 238, representing 99·3 per cent of the whole, a second of mass number 235, to the extent of only 0·7 per cent, and a third of mass number 234, which is present in such minute amounts that we can almost ignore it. For reasons which will appear later, it became highly desirable either to separate weighable amounts of the 235 kind or to increase the percentage of this isotope in a specimen of uranium. The magnitude of this problem, if even only a few grams of uranium 235 are to be collected, can be realized from the fact that in the early days Nier, an American physicist, using vapour from uranium bromide in a mass spectrograph, could collect less than a microgram of separated uranium 235 per 16 hour day.

In the successful separation of comparatively large amounts of individual isotopes of uranium and of other elements, use was made of several different methods, all of which had been known in principle before the uranium problem became urgent. A brief reference will be made to three of these.

(a) **Electromagnetic method**—*the calutron*—Somewhat similar in principle to the mass spectrograph, the calutron makes use of a beam of ions which, after being speeded up by an electric field, traverses a magnetic field powerful enough to cause the ions to move in circular paths. The reason for this deflection is explained in detail in section 13.7. Since the amount an ion is deflected by a magnetic field depends on its mass, an ionic beam containing a mixture of isotopes will give rise to different paths, one for each isotope, somewhat as shown in Fig. 4.7. Hence by suitably placing an obstacle with a narrow opening in it, a single isotope can be collected in a receiver placed beyond the opening.

For the separation of the very large amounts of uranium 235 needed in the development of atomic energy, a mass spectrograph (or spectrometer) is not suitable, the method of gaseous diffusion described below being used. The spectrometer, however, is extremely valuable for routine automatic analysis of the degree of concentration of uranium 235 and of other isotopes. Both at Harwell and at the U.S. Oak Ridge National Laboratory it is also used to a marked degree for the production, usually in small but usable quantities, of

many isotopes, most of them stable. A recent (in 1955) article in *Nature* states that at Oak Ridge more than 200 enriched isotopes of some 50 elements have been produced. At Harwell, isotopes of 37 elements have been separated in quantities ranging from micrograms of calcium 46 to 30 grams of iron 56. One main object of this work is to prepare targets suitable for nuclear bombardment.

For the operation of large amounts of uranium 235, the more practical method makes use of diffusion.

(*b*) **Gaseous diffusion method.** This method is based on the fact that the rate at which a gas diffuses through very tiny openings depends on the mass of its molecules, being, in fact, inversely proportional to the square root of the mass. Hence, if we have a mixture of two isotopes of an element in the gaseous state, in a vessel with a wall containing very small openings—a *porous barrier*—the isotope of lighter mass will diffuse through the wall or barrier more rapidly than the heavier, and a partial separation of the two will result. It is interesting to note that Aston, in early attempts to separate the isotopes of neon, used clay piping as his barrier. The actual amount of separation resulting from diffusion through a single barrier is slight, and a cascade process using many units is necessary for any marked degree of separation. Actually, the cascade method has been used to obtain nearly pure amounts of neon 22.

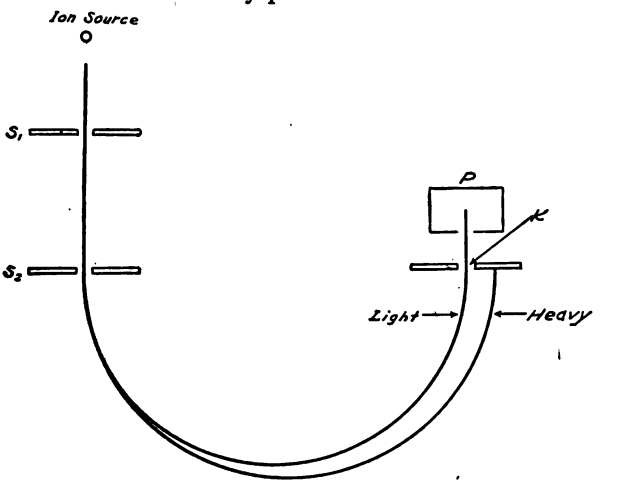


FIG. 4.7. A mixture of the ions of the two or more isotopes of an element, when speeded up by an electric field, emerges from slit S_2, each with its own momentum. In passing through a strong magnetic field, the ions are separated, each kind traversing a circular path slightly different from the others. By suitably placing a slit as at K in the figure, any particular isotope may be collected. (Diagram from Smyth Report.)

After several years of intensive research by many men and many organizations the gaseous diffusion method was used, ultimately on a factory scale, for the preparation of uranium enriched in the 235 variety. One of the major problems in this work was the construction of a suitable porous barrier, because it had to be of a material not attacked by the gaseous compound uranium hexafluoride, and it had to have holes not larger than 4×10^{-7} inch. This and many other problems were successfully solved and, in 1945, after some years of hard, and at times discouraging, work, a satisfactory diffusion plant was operating at the Clinton Engineering Works in Tennessee.

In Britain, in 1950, at Capenhurst, Cheshire, work was begun on the construction of a large scale diffusion plant capable of separating uranium 235 of almost 100 per cent purity. This plant is now (1954) in operation and " producing a satisfactory output ".*

(*c*) **The centrifuge.** This method employs the principle of the cream separator. If a system containing a mixture of two isotopes is rotated at very high speeds, a partial separation is accomplished because the concentration of the lighter isotope increases near the axis of the rotating system, that of the heavier near the periphery. This method was also successfully used in the search for the release of nuclear energy, but it was not employed for any large scale production.

4.10. Heavy Water. No explanation will be given of two or three other methods which have been used to some extent in the separation of isotopes but, before leaving the subject, a brief reference is made to the principle utilized in one method of manufacturing heavy water.

Shortly after the discovery of deuterium, the heavy isotope of hydrogen, it was found that, when ordinary water is decomposed by electrolysis into hydrogen and oxygen, the residual water left after a considerable amount of water has been decomposed contains a higher percentage of heavy water than it had originally. It then became obvious that, by collecting the residues from a number of electrolytic devices and decomposing the collected lot, now richer in the heavy variety, until the residue after the second stage was still further enriched, and by continuing such a process for several stages, heavy water of high concentration could finally be obtained.

* Quotation from *Britain's Atomic Factories*, K. E. B. Jay, H.M. Stationery Office, 1954.

PROBLEMS AND QUESTIONS

1. Describe the construction and operation of a simple type of tube by means of which, by positive ray analysis, a beam of ions can be analyzed into its constituents. Explain fully.

2. An electron and a singly-charged positive ion fall through equal potential differences. Compare (i) the energy, (ii) the velocity acquired by each.

3. Singly-charged positive ions of ordinary hydrogen and of deuterium fall through equal potential differences. Compare (i) the energy, (ii) the velocity acquired by each.

4. Briefly describe two ways of separating stable isotopes of an element.

5. Indicate how the mass spectrograph can be used to compare atomic weights.

6. Explain how the atomic weight of an element like chlorine can be evaluated using the mass spectrograph.

7. Explain the difference between the physical and the chemical methods of establishing a scale of atomic weights.

CHAPTER V

ROENTGEN TUBES

5.1. Two Types of Tubes. In section 3.10 it was pointed out that X-rays originate when a beam of fast-moving electrons is suddenly stopped on striking a target of hard metal. To obtain a suitable beam of electrons two important methods have been used, with two corresponding types of X-ray tubes. In the first type, the gas tube, a residual vacuum is left at such a pressure that a well-developed beam of cathode rays is projected from the cathode, while at the same time positive ions move toward this electrode. In the second type, the hot filament tube, electrons are emitted from a heated filament which also functions as the cathode of the tube. In this type the vacuum must be so good that there is no cumulative ionization by collision, or, in other words, so that there is no appreciable electron flow arising from this cause. As gas tubes are now almost obsolete attention is confined to hot filament tubes. To explain their construction, the information given in section 3.6 about thermionic emission must now be amplified.

5.2. Thermionic Emission. Fig. 5.1 represents a highly exhausted glass bulb provided with three electrodes or terminals, 3

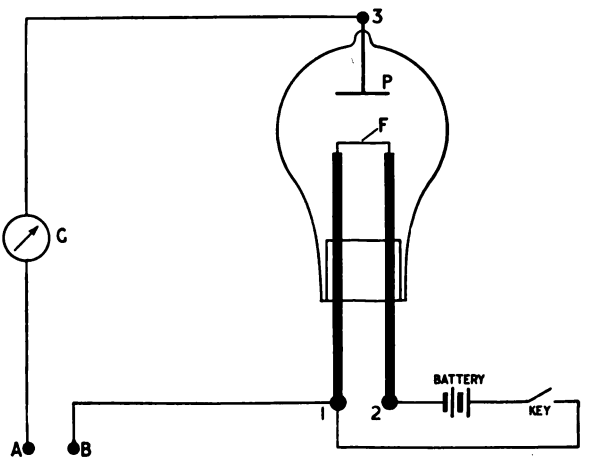


FIG. 5.1. A thermionic current flows across the highly evacuated tube, when the filament *F* is hot and is negative.

joined to an inner sheet of metal P which we shall call the plate; 1 and 2 to the ends of a filament F of fine wire, tungsten, for example. Terminals 1 and 2 are connected to a storage battery by means of which current may flow through the filament and heat it to incandescence. A second circuit including a galvanometer G or a milliammeter is made by joining the 110 d.c. terminals A and B to 1 and 3 as illustrated in the figure. A deflection of G will then indicate a current flowing around the circuit A to G to 3 to plate to filament to 1 to B. Is there any such current? We distinguish two cases. (1) With filament cold, that is, key open, it is found that, no matter what the polarity of A and B is, no current is indicated by G. (2) With the filament incandescent (key closed), however, if B is negative, a marked current is indicated, whereas if B is positive, no current passes.

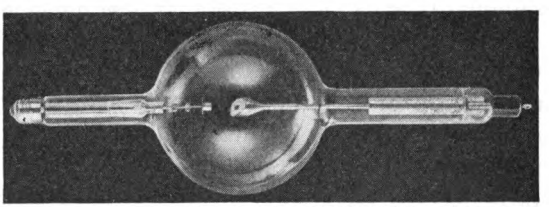
Evidently, therefore, a current passes through such a tube when the filament is hot and when it is negative. Now, what is the explanation? It is found in the fact that any hot piece of metal is a source of electrons. At the surface of metals a process somewhat akin to evaporation goes on, as a result of which, at high temperatures, there is a copious emission of electrons known as a *thermionic emission*. In the above tube, therefore, the hot filament liberates electrons; if the filament is negative, and the plate positive, since negative repels and positive attracts negative electricity, these electrons are driven across the vacuum space. There is, therefore, a current of electricity which, in this case, consists of a stream of negatively charged electrons. If the filament is positive, however, because of the attraction of positive for negative, the electrons cannot escape from the filament and no such current exists.

It is well to note that, although the electrons move from the filament to the positive plate, the direction of the current is from plate to filament. This is because of the convention that current direction is that in which positive electricity moves. Negative electrons coming out of a conductor is equivalent to positive electricity flowing into it.

5.3. Hot Filament Rectifiers. It should now be evident that if the supply voltage is *alternating*, a stream of electrons will cross the tube only during the half-cycle when the filament is negative. In other words, an intermittent but unidirectional current flows in the circuit containing G, although an alternating voltage is applied. A tube of this sort, frequently called a *diode*, therefore, is an excellent rectifier and has many practical applications, as will be seen in the next chapter.

5.4. Hot Filament X-ray Tube. Dr. W. D. Coolidge, of the General Electric Research Laboratory, was the first scientist to construct an X-ray tube of the hot filament type. A tube of this kind differs from the gas tube, not because X-rays originate in any different manner, but because the stream of high speed electrons has its origin in an incandescent filament. Although there are many varieties of hot filament tubes, certain fundamental principles are utilized in nearly all of them, and these the student should clearly understand.

To begin with, we cannot do better than examine the construction and operation of the Universal Coolidge tube, one so satisfactory that, after many years of service, it is still on the market in only slightly altered form. Figure 5.2 is an actual photograph. This type, like almost any other, consists essentially of a filament F, Fig. 5.3, which acts also as the cathode, and the anode A. To heat the filament, an independent circuit, called the *filament circuit*, is necessary. In the original arrangement a storage battery B_1 and B_2 was used as the



Courtesy General Electric X-ray Corporation

FIG. 5.2. The Coolidge Universal Hot Filament X-ray Tube.

source of supply for the circuit. In the arrangement in actual use, as shown in Fig. 5.4, a branch from the a.c. mains supplies a small filament step-down transformer, the secondary of which is connected in series with the filament. Although this arrangement is more convenient it has one disadvantage. Voltage fluctuations on the line will cause corresponding fluctuations in the filament and consequently, as we shall see later, alter the milliamperage through the tube.

To give the necessary high speed to the liberated electrons the high tension voltage is applied to the tube in the usual way, the hot filament being, of course, negative. The stream of electrons focused by a method explained in section 5.6, strikes the target at the *focal spot*, the target in this type of tube being the inclined face of a solid rod of tungsten which forms the anode.

The complete circuit, therefore, includes (1) the high tension circuit (2) the filament circuit. A transformer supplies the high tension, the alternating voltage being rectified either by the tube

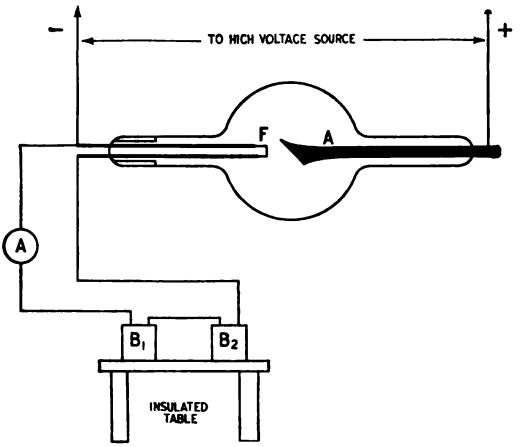


FIG. 5.3. Simple connections when filament of a hot filament X-ray tube is heated by means of a storage battery.

itself or by valves in ways explained in Chapter VI. Since the filament circuit is raised to the high potential of the cathode, it is necessary to insulate the filament transformer. An ammeter (not a milliammeter) in the filament circuit enables the operator to read the value of the current heating the filament, current strengths being altered by a control such as a variable reactance. Before discussing

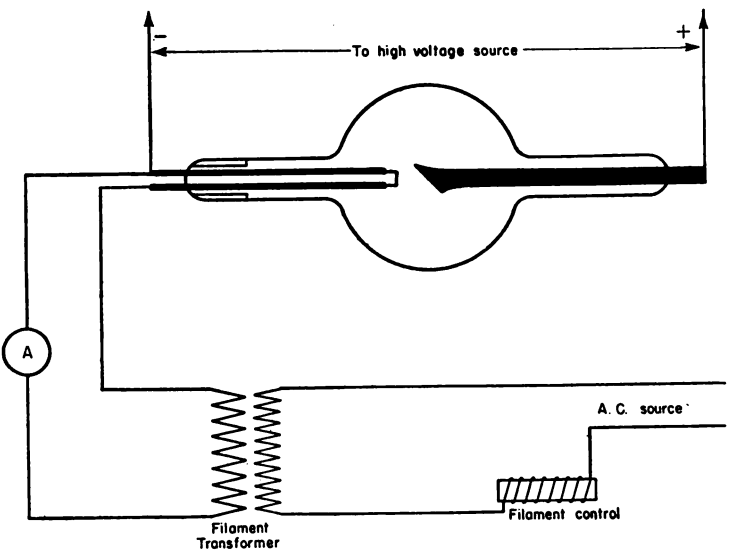


FIG. 5.4. Simple connections when filament is heated by a step-down transformer.

details of control, it is desirable next to examine one or two further points in connection with the tube itself.

5.5. Preparation of Hot Filament Tubes. To obtain the necessary high vacuum and to eliminate as much as possible all traces of residual gas, elaborate precautions are taken. Vacuum workers know that small amounts of gas not only cling to solid surfaces, but are also embedded right inside all materials. For example, if a glass vessel is highly exhausted and sealed off without any prelininary heating, a very slight rise in temperature will release gas from the glass and the vacuum will very quickly deteriorate. In high vacuum work, therefore, such as in the exhaustion of hot filament tubes, a very careful process of degassing must be carried out. Into details of this process it is not necessary to go, but we may point out that, with the exhaust pump running " full blast ", all metal parts are heated to a high temperature (by electromagnetic induction), the tube itself is baked in an oven at 400° C. or 500° C., and a current put

TABLE V

Gas	Pressure in Microns Mercury
Helium - - -	5·0 to 10·0
Hydrogen - - -	4·0 to 8·0
Nitrogen - - -	0·5 to 1·0
Water Vapour - -	0·2 to 0·5
Mercury Vapour - -	0·01 to 0·03

through it under operating conditions. Finally the tube is sealed off, after gases occluded in the glass and the metal parts have been removed as completely as possible. One reason for preventing the temperature of a target rising to too high a value at the focal spot is to avoid the liberation of gas which would otherwise result.

Since a perfect vacuum cannot be obtained, there is always a very slight amount of residual gas, and hence there is always the possibility of a few stray positive ions being formed. Provided the gas pressure is well below the value where cumulative ionization by collision takes place (see section 3.8), no harm is done. This value naturally depends on the type of tube used, but some idea of its magnitude will be had from Table V. This table, taken from a paper on X-ray tubes by Gross and Atlee, of the General Electric Corporation, gives the maximum permissible pressures in microns* of mercury, for satisfactory operation of a 85 kVp (kilovolts peak), 30 ma tube.

* 1 micron = 0·001 mm.

5.6. Focusing. In section 5.4 a brief reference was made to the *focal spot*, the small area on the face of the target against which the beam of cathode rays or electrons strike. In the gas X-ray tube, the beam is focused on this spot partly because of the shape of the cathode, partly because the walls of the tube in the neighbourhood acquire a negative charge and this charge exerts a repulsive effect on the beam of electrons. In hot filament tubes focusing is brought

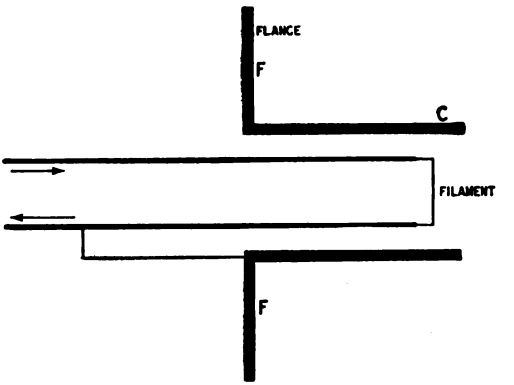
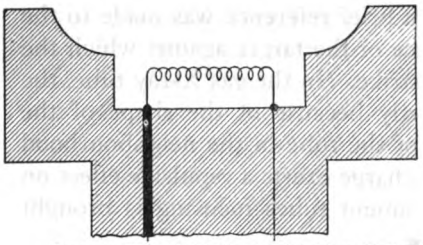


FIG. 5.5. Focusing device in the universal Coolidge Tube.

about partly because the electric field which exists between cathode and anode directs the beam of electrons towards the target, but more so because of the actual structure of the cathode itself. In the universal tube, for example, the filament, wrapped into a small flat spiral, is surrounded by a concentric metal cylinder, one end of which projects a little beyond the filament, as shown in Fig. 5.5. The other end is attached to the flange *F*. As the cylinder and flange, and the filament itself are all in electrical contact with the negative high tension terminal, a repulsive force acts on the liberated electrons. A somewhat similar arrangement is shown in Fig. 5.6, a diagram taken from literature of the Philips' X-ray works. Figure 5.7 is a close-up photograph showing the actual relation of the filaments, in a special double-filament tube, to the surroundings. By using filaments of different shapes and adjusting the relative position of the parts, focal spots of different sizes are obtained.

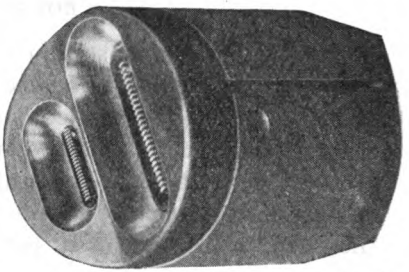
" The focal spot size, shape, and distribution can be controlled almost entirely by the filament size, shape and position relative to the rest of the cathode structure." (Gross and Atlee.)

Sometimes, for a reason which will be more fully explained in section 8.6, instead of using an open cathode as in Fig. 5.6, the



Courtesy Philips' Gloeilampenfabrieken, Holland

FIG. 5.6. A focusing arrangement in a hot filament tube.

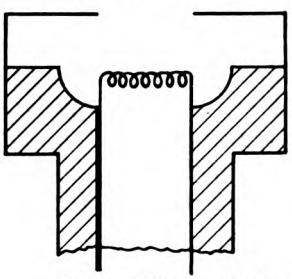


Courtesy General Electric X-ray Corporation

FIG. 5.7. A close-up view of filaments in a double filament tube.

cathode is shielded as shown in Fig. 5.8, its face being extended forward by the metal projection. When a tube with such a cathode is used with pulsating voltage, the output of X-rays for the same mean current as in an unshielded tube is considerably increased. A tube so equipped is sometimes described by the term " grid action ".

5.7. Methods of Cooling a Target. In X-ray tubes only a very small fraction of the energy delivered to a standard tube is used for the production of X-rays, almost all of it going into heat. In most tubes to be used with appreciable amounts of power, therefore, cooling means are added. Several methods have been used. Sometimes use is made of the high thermal conductivity and the high specific heat of copper by making a substantial part of the anode of this metal.



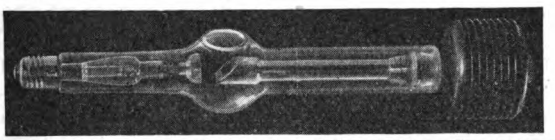
Courtesy Philips Electrical Ltd.

FIG. 5.8. A shielded cathode.

Additional cooling is often brought about by attaching to the end of the anticathode (or anode) outside the tube, sheets of metal which because of their large surface are good radiators of heat. (See Fig. 5.17 and Fig. 5.9.) Cooling is also often accomplished by the use of water-cooled targets, a very efficient method because circulating water continuously carries away the heat developed. Even if the water is not renewed by inlet and outlet pipes, its temperature cannot rise above 100° C., hence as long as there is water in the water cooler attached to the anode (see Fig. 5.10 and Fig. 5.11), high temperatures are not possible. Still another method consists in the use of an anode so massive that a large amount of heat is necessary to increase its temperature an appreciable amount. (See Fig. 5.12.)

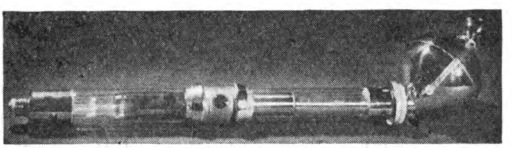
5.8. Control of Tube Current. In the hot filament tube the

current consists solely of the stream of negative electrons liberated from the filament. How is the magnitude of this current controlled? In order to understand the answer to that question it is well to recall that an electric current is measured by the total quantity of electricity passing each second any " point " on the circuit. If, therefore,



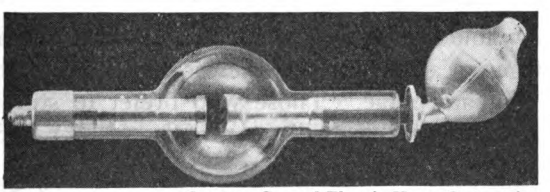
Courtesy General Electric X-ray Corporation

FIG. 5.9. A radiator X-ray tube.



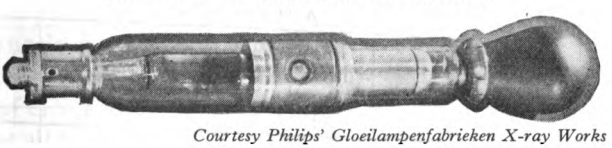
Courtesy Philips' Gloeilampenfabrieken X-ray Works

FIG. 5.10. A water cooled X-ray tube.



Courtesy General Electric X-ray Corporation

FIG. 5.11. A water cooled X-ray tube.



Courtesy Philips' Gloeilampenfabrieken X-ray Works

FIG. 5.12. An X-ray tube with a massive anode and blackened cooling sphere.

more electrons are transferred every second from the filament to the target, the tube current will be greater. Now work on thermionic emission has shown that the higher the temperature of the hot filament the greater the supply of electrons. *The milliamperage through the tube, therefore, can be increased simply by increasing the filament heating current.* But, it is asked, where does voltage come in? That can be answered with reference to experimental results such as given in Tables VI and VII (taken from General Electric Co. literature).

The numbers in Table VI refer to a tube whose filament current was kept constant at 3·6 amperes.

Greater and greater voltages were applied to the tube, and for each value the corresponding tube current was measured. It will be

TABLE VI

FILAMENT CURRENT 3·6 AMP

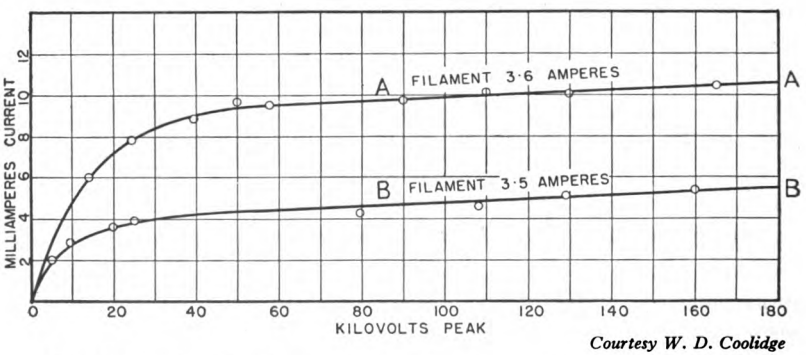
Kilovolts	Milliamperes
3	2·0
8	4·0
15	6·0
30	7·8
40	8·8
58	9·7
90	9·8
110	10·0
130	10·0
165	10·5

TABLE VII

FILAMENT CURRENT 3·5 AMP

Kilovolts	Milliamperes
5	2·0
10	2·5
20	3·7
25	4·0
60	4·2
80	4·3
108	4·4
130	5·0
150	5·0
160	5·2

noticed that, while at first the tube current increases with increasing voltage, a stage is reached at which increase in voltage produces slight increase in milliamperage. Those who prefer to study results in graphs rather than in tables will see that Curve *A*, Fig. 5.13, shows



Courtesy W. D. Coolidge

FIG. 5.13. Graphs showing saturation tube current for two different filament currents.

the same result even more clearly. In Table VII and Curve *B*, Fig. 5.13, the same result is shown for a different filament current, the only difference in the two cases being that the maximum tube

current in the latter is greater. Experiment tells us, then, that *corresponding to each filament current, there is a maximum value of the tube current, which is independent of the applied voltage.* The explanation of this maximum current—called the *saturation current*—is simple enough. The available supply of electrons from a hot filament depends on its temperature and therefore on the magnitude of the filament current. Evidently no more electrons can be transported across the tube per second than are liberated each second from the filament.

The student may wonder why all the liberated electrons should not be transported to the anode at low as well as at high voltages. The chief reason for this lies in the existence of what is called the *space charge.* Suppose a filament is heated *without* the application of a potential difference between filament and anode. The evaporated electrons then form a cloud of negative electricity in the space immediately surrounding the filament. Since negative electricity repels negative, due to this space charge there is a strong repulsive force which not only prevents the emission of further electrons but also drives electrons back into the filament. When a comparatively small voltage is applied across the electrodes (with anode positive), the electrons move to the anode and a current is recorded. But with low voltages the speed of the electrons is not great, and they are present in sufficient numbers in the region between the electrodes to continue to exert a backward force on those electrons near the filament. For a given field between the electrodes and a fixed filament temperature, a balance is reached when electrons are emitted from the filament at such a rate that the force on those near the filament due to the space charge cancels the applied electric field.

As higher and higher voltages are applied, a greater and greater number of electrons is transported each second across the tube until ultimately all the electrons emitted by the filament reach the anode. As already noted we have then the saturation current. Hot filament X-ray tubes may therefore be designed so that control of the tube current is exercised in two ways: (*a*) by total emission of electrons from the heated filament; (*b*) by the utilization of space charge. If the applied voltage is sufficiently high to ensure saturation current, the tube current depends only on the temperature of the filament, that is, on the total electron emission. In this case the tube current is readily altered by changing the filament current, whose magnitude is read off the ammeter in the filament circuit. It is, then, highly desirable that the operator of a particular tube should know the tube

(saturation) current corresponding to each ammeter reading. Such information he can readily obtain for himself by taking, for each of several filament current values, the saturation tube current. He will

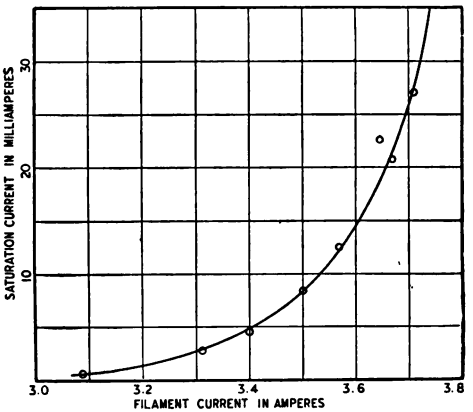


FIG. 5.14. Graph showing how the saturation tube current varies with the filament current.

then have a table similar to Table VIII (a copy of some actual results taken from an early paper by Dr. W. D. Coolidge).

By plotting these results an extremely useful curve similar to that in Fig. 5.14 will be obtained. Figure 5.15 is a copy of a similar curve for a Universal tube taken from advertising literature.

When a tube current is controlled by a space charge, it must be operated on the curved part of the graphs reproduced in Fig. 5.13. In other words, the filament temperature must be sufficiently high that, within the range of voltages utilized, saturation current is never attained.

TABLE VIII

Filament Current	Tube Current
3·09 amp	0·6 ma
3·31	2·5
3·40	4·4
3·50	8·2
3·57	12·6
3·67	20.7
3·65	21·8
3·71	27·0
4·13	35·4

Although in emission control an increase in voltage beyond the value necessary to produce saturation does not alter the magnitude of the tube current, it does alter the nature of the beam of X-rays. (See section 7.8.) Moreover, an increase in voltage beyond this point means an increase in the electrical power supplied the tube. Care should be exercised, therefore, not to exceed the maximum voltage and maximum power which is safe to use with a particular tube. (See section 5.13.)

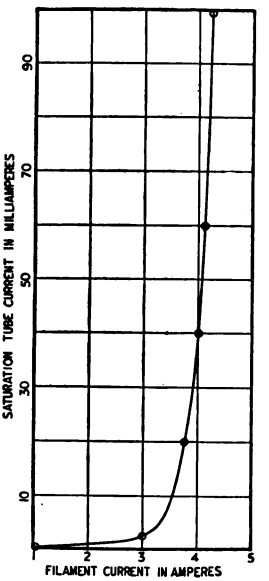


FIG. 5.15. Graph showing that a slight change in filament current may cause a marked change in tube current.

5.9. Voltage Stabilizer. In connection with the relation between filament current and tube current it is important to note that a very slight change in the filament current may produce a big change in the tube current. If we take some actual numbers from the curve of Fig. 5.15, we see that with filament current 4 amperes, the tube current is 40 ma, while an increase to $4\frac{1}{4}$ amperes raises the tube current to 100 ma. This has an important practical aspect. Should the filament current fluctuate, there will be marked changes in the tube current—as much as a 25 per cent change for a 1 per cent change in filament current. Obviously this is not desirable. The remedy is to use a voltage stabilizer. (See section 2.14.)

5.10. X-ray Protection and Metalix Tube. Although a detailed discussion of the properties of X-rays has not yet been given, probably all medical students are aware that unwanted X-rays falling on the body of either patient or operator may have serious injurious effects. It is very necessary, therefore, to provide adequate protec-

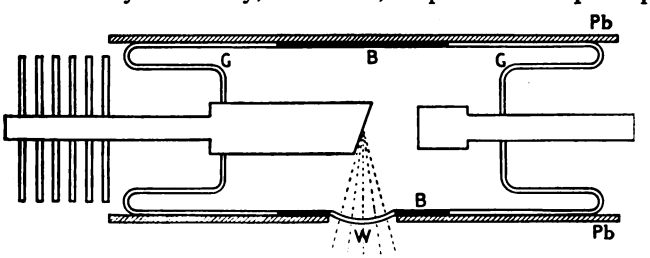
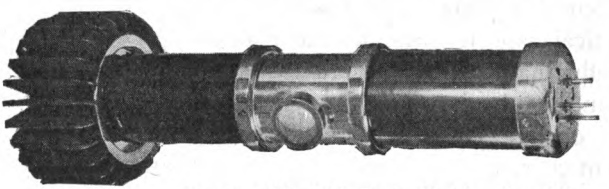


FIG. 5.16. Schematic diagram of metalix X-ray tube.

tion against such rays. To do this many precautions must be taken, but obviously the first step is to see that, if possible, the beam of rays leaving the tube is restricted to a narrow bundle. To some extent this can be accomplished by surrounding the bowl of the tube with some material which absorbs all or nearly all the rays which strike it. An opening, of course, must be left to allow the passage of the useful cone of rays. Some of the earlier tubes were so covered with a protecting covering of rubber impregnated with lead oxide, lead being an excellent absorbing material for ordinary X-rays, or with a protecting bowl of thick lead glass.

A radical departure in X-ray tube protection and in tube design was embodied in the so-called *metalix* tube, first put on the market by the Philips' Gloeilampenfabrieken X-ray Works, Holland. Although Coolidge, as early as 1915, had experimented with a metal tube, the metalix was the first which used the principle of metallic protection in the tube itself, to be put in the hands of radiologists. The main features of this type will be understood by a study of Fig. 5.16 and Fig. 5.17, which shows its general appearance. The tube consists essentially of a cylinder of chromium-iron alloy, *B*, in Fig. 5.16, which at each end is sealed to the re-entrant glass cylinders *G*, *G*.



Courtesy Philips' Gloeilampenfabrieken X-ray Works

FIG. 5.17. The Metalix X-ray Tube.

A window *W* placed opposite the target permits the passage of all but the softest X-rays. The protection provided by the central metal cylinder is greatly increased by a layer of lead which surrounds it. In addition, the somewhat massive anode and the cathode assist in cutting off unwanted rays, particularly longitudinally, and a layer of bakelite, which forms the casing of the whole tube, adds more protection. At the same time this casing shields the bright light of the incandescent filament and mechanically is a protection to the glass.

The general Electric X-ray Corporation have a tube, somewhat similar in appearance, in which an all-glass cylindrical envelope is surrounded by a removable casing, providing both protection and insulation.

5.11. Line Focus. The metalix tube introduced another new feature in X-ray tubes, and that was the use of a linear instead of a circular spot, a suggestion originally made by Goltze. To understand the significance of this change, the student must be clear about two points. The first has to do with the intense local heating generated at the focal spot. Concerning this, it should be evident that the *larger* the area* over which this heat is developed, that is, the larger the focal spot, the lower the resulting temperature and the less the danger of destroying the tube. The second point concerns the relation of the size of the focal spot to the sharpness of the picture when the shadow of an object is observed on a fluorescent screen or a photographic plate. If the student will think of X-rays as invisible light (as indeed they are), he will realize that the *smaller* the dimensions of the source of the beam, the sharper the shadow picture of an object, unless it is a flat one placed close to the screen or plate. Figure 5.18, which

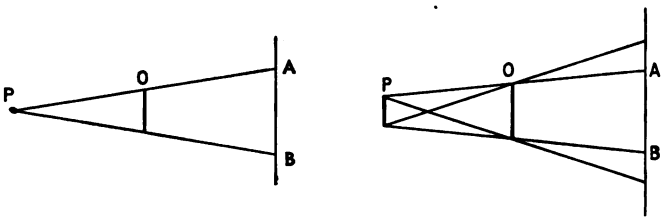


FIG. 5.18. In (*a*) the small source of light *P* casts a sharp shadow of the obstacle *O*; in (*b*) the broad source gives rise to the deep shadow *AB* surrounded by a penumbra.

illustrates the point, will be very familiar to anyone who has taken a course in elementary light. For sharp detail, therefore, the focal spot should be as small as possible. (The question of sharpness is discussed in greater detail in Chapter IX.)

But if the focal spot is very small, the power input (the " load " on the tube) must be kept small because of the temperature effect, and frequently it is not desirable to restrict the power. For example, the smaller the power, the longer the exposure when X-ray photographs are made; and in many cases it is necessary to have short exposures.

Designers of X-ray tubes, therefore, were faced with the problem of combining sharp shadows with short exposures, or in other words, of retaining the equivalent of small focal spots with adequate power input. The problem was solved in two ways, (1) by the use of a *line* focal spot, as in the metalix tube; and (2) by the use of a rotating anode (see section 5.12).

* See, however, section 9.8.

In the metalix tube, and many others since placed on the market, a linear filament is so placed in relation to the surrounding cathode that a focal spot of the shape *AB*, Fig. 5.19*a*, is formed on the face of the target *TT'*, this face being inclined to the axis of the tube at an angle of 71°, not the 45° previously used with circular spots. Now, although the actual length of the focal spot is several times its width, to an observer looking along the central part of the beam of X-rays, its *effective* length, in so far as its ability to cast shadows is concerned is only *CD*. Thus, although the actual total area of the spot is as illustrated in Fig. 5.19 *b*, its effective " shadow-casting " area is more like Fig. 5.19 *c*. Because of the greater actual area, it is possible to use an electric load on the tube considerably greater than when a spot of actual area Fig. 5.19 *c* is formed on a 45° face target.

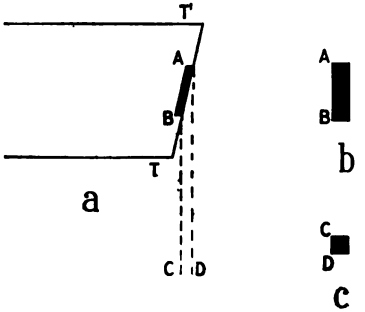


FIG. 5.19. *AB* represents the actual area of the focal spot, *CD* the projected area looking along the dotted lines.

5.12. Rotating Anode. To permit the use of still higher amounts of power, tubes with revolving anodes have been designed by the Philips' X-ray Works, the General Electric X-ray Corporation, Machlett Laboratories and others. In tubes of this kind, although the focal spot is stationary and of the rectangular shape shown by the black spot *A* in Fig. 5.20, because the anode is kept in rotation, the area over which heat is developed is the annular space shown in this figure by the dotted circles. In the General Electric tube illustrated in Fig 5.21 and Fig. 5.22, a disc of tungsten is rotated at a speed of 3,000 r.p.m. by an induction motor whose stator is outside the evacuated part of the tube. The electron beam strikes the bevelled edge of this disc, clearly shown in Fig. 5.21, giving rise (along the centre of the useful beam of rays) to an *effective* spot which, in one tube, is 2 mm × 2 mm when the actual area over which heat is produced is 7 mm (the length of the actual spot) × 190 mm (the mean circumference of the annular area). With such a tube, therefore, high power inputs are possible without losing the advantages of a small focal spot. For example, with a certain tube of this type,

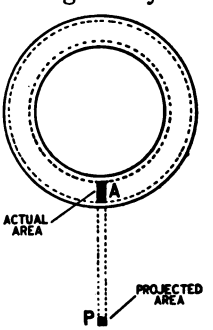
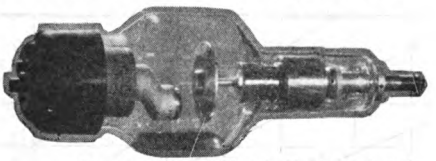


FIG. 5.20. The heavy circles represent the bevelled edge of a rotating anode, *A* being the actual area of the focal spot.

with an effective focal area as small as 1 mm × 1 mm, it is possible to use the same power input and same exposure time as for an effective spot of 3·8 mm × 3·8 mm with a stationary anode.



Courtesy General Electric X-ray Corporation

FIG. 5.21. A rotating anode tube.

5.13. Rating. From the preceding sections, it should be evident that it is highly desirable to know the maximum power which may safely be supplied to a tube, as well as the time this or any lesser amount may be used. This is what is meant by *rating*.

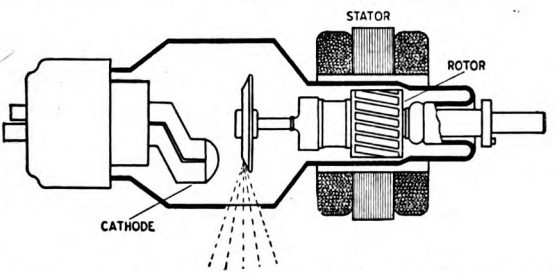
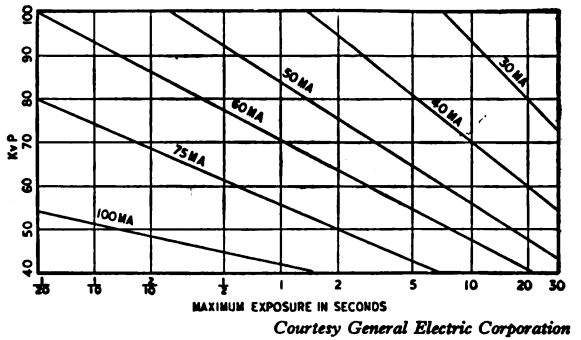


FIG. 5.22. Diagram showing the essential features of a rotating anode tube.

In considering this question, the student should recall again that most of the energy supplied by an X-ray tube goes into heat and that the amount of energy is proportional to the product voltage × current × time. (Recall *VIt* joules in ordinary d.c. circuits.) If, then, a radiologist is told that a certain tube can be safely operated for 30 seconds, at 85 kilovolts peak (kVp) with a current of 30 ma, he has a rating which is simple and definite. But it does not give enough information. He may want to know how long the tube may be used with 5 ma at the same or some other kVp, or he may wonder how the rating is altered when a change is made in the operation of the tube from a constant voltage generator to one in which energy is utilized only in alternate half-cycles (see next chapter).

Modern practice gives the answer to such questions because the manufacturer supplies charts from which exposure times can be read off for corresponding voltage and current values, a separate chart

being supplied for each type of supply equipment, such as full-wave, half-wave. (See next chapter.) Figure 5.23, taken from General Electric literature is an example of one of the actual charts for the



Courtesy General Electric Corporation

FIG. 5.23. A typical rating chart.

Coolidge Tube unit DX2–4·5. It applies when a 2·0 × 2·0 mm focal spot is used and the tube is operated on full-wave rectified equipment. To make sure that he understands the use of such a chart, the student should check the values given in Table IX. These are read off one of the graphs of Fig. 5.23.

TABLE IX

kVp	ma	Exposure Time
100	60	1/20 sec.
86	60	1/5
70	60	1
54	60	5
40	60	20

It is important to note that, although the exposure time in the first line of this table is 400 times less than that in the last line, the power supplied the tube is only 2½ times greater. In other words, it is a bad mistake to assume that if it is permissible to expose for 1 second with a certain amount of power, that five times that amount could be used for a fifth of a second. Time must be allowed for heat developed to be removed, hence a greater and greater limitation is placed on the permissible power the shorter we make the exposure.

5.14. Shockproof Tubes. In section 5.10 reference was made to the necessity of protecting a tube so that X-rays do not leave it in unwanted directions. Protection against electrical shock arising from

contact with high tension wires is equally important. For a great many years both the electrical leads to a tube and its terminals were unprotected and there was always present very real danger of bad electrical shocks to patient and operator because of accidental contact with these conductors. Nowadays, although this danger is still often present, many tubes are *shockproof*, that is, they are so protected that it is perfectly safe to put one's hand on the casing in which the tube is housed, because the casing is at ground potential.

Figures 5.24 and 5.25 illustrate the general appearance of two such tubes. The means of providing protection is extremely simple. The

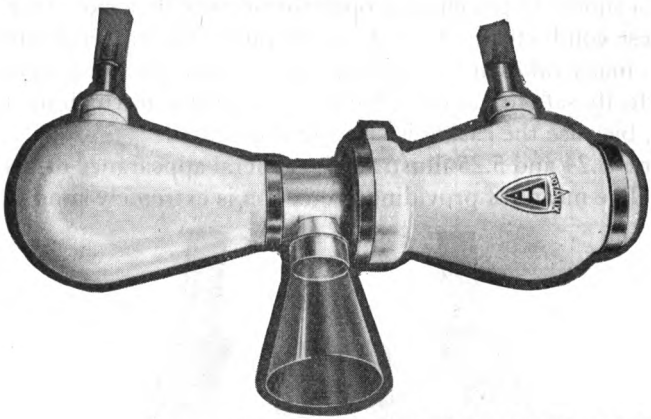
Courtesy General Electric X-ray Corporation

FIG. 5.24. A shockproof X-ray tube.

tube proper is enclosed in a metal case which is grounded, and the high tension leads to the tube are surrounded by heavy insulating material around which a flexible grounded metallic casing is wrapped.

5.15. Oil-immersion. The design and general arrangement of the earthed casing of a shockproof tube must be such that there is no danger of breakdown sparking between any high-tension part of the tube and the surrounding casing. In Fig. 5.25, a Philips' tube, this is done by suitable design of the parts. In Fig. 5.24, a General Electric tube, the space between the tube and the casing is filled with oil, the whole being hermetically sealed. Because of its insulating properties oil minimizes the space necessary between high tension and earthed

parts. The use of oil also makes the arrangement independent of atmospheric conditions, and, moreover, " oil is superior to air as a heat absorbing and cooling medium."



Courtesy Philips' Gloeilampenfabrieken X-ray Works

FIG. 5.25. A shockproof X-ray tube.

In this connection it is interesting to note that the General Electric Corporation have units in which not only the X-ray tube, but also the high voltage equipment, transformer and all, are enclosed in oil in a grounded container.

5.16. Low Voltage Tubes. As will be seen in Chapter VII, the kind of X-rays leaving a tube operated on low voltages, in the range 5 to 50 kV, are feebly penetrating and hence are suitable for the treatment of skin diseases. Such tubes are sometimes given the name *Grenz*. At this stage a brief reference is made to a tube of this kind designed by

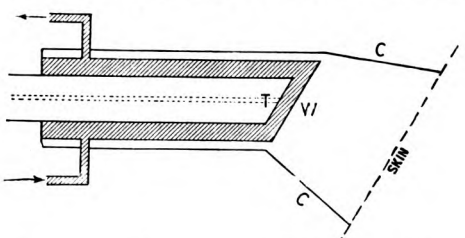
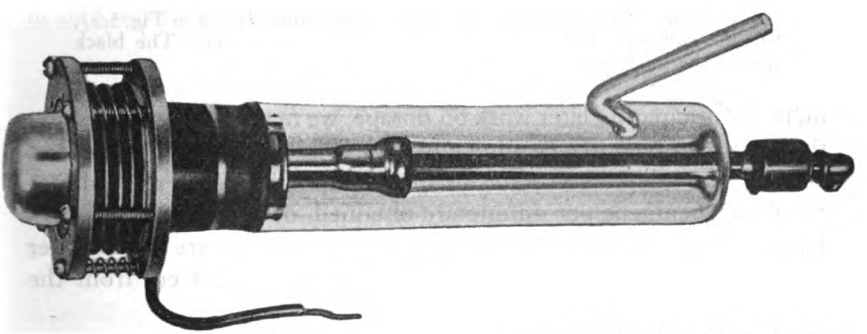


FIG. 5.26. The target and treatment end of a Chaoul therapy tube.

Chaoul, one of the pioneer workers in this field. The important feature is the anode end. The electrons, indicated by the dotted lines in Fig. 5.26, pass down an earthed metal cylinder and strike at its far end a

target *T*, made of gold-plated nickel, only 0·15 mm thick. Water circulating in a narrow region around the target end of the cylinder effectively cools the target. Because of the extremely small thickness of the target, the X-rays generated pass through it with slight absorption, as well as through the 2 mm thickness of water between the target and the outer wall *W*. A conical applicator *CC* slipped over the end of the tube rests on the skin of a patient, the rays striking the skin at focal distances of only a few centimetres. For obvious reasons such a tube is sometimes called a *contact tube* and its target a *transmission target*. In this tube, as originally used by Chaoul, the voltage was of the order of 10,000 volts.

5.17. Low Voltage Tube Emitting Rays of High Intensity. Machlett Laboratories, Inc., recently have put on the market an X-ray tube designed to produce X-ray beams of intensities thousands of times greater than any which have been described in this chapter. A brief reference will be made to one or two novel ideas utilized in

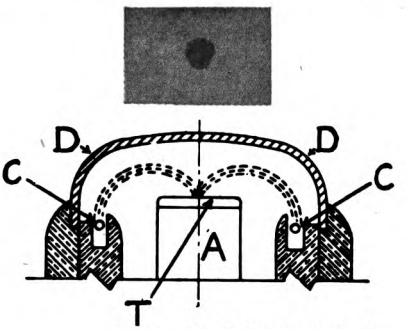


Courtesy Machlett Laboratories, Inc.

FIG. 5.27. Photograph of a low voltage high power tube of new design.

this tube, a photograph of which is reproduced in Fig. 5.27. The dome at the extreme end of the tube, represented by *DD* in Fig. 5.28, is an approximately hemispherical window made of the metal beryllium, a material which, as will be seen in Chapter VII, absorbs X-rays of long wave lengths to an extremely slight degree. The beryllium window is at ground potential and is in electrical contact with the cathode which is a heated filament, annular in shape, being represented by *CC* in Fig. 5.28. The water-cooled anode *A* is at a potential of some 60 kilovolts above ground, the face of the target *T* extending beyond the level of the cathode. Because of the electric field between the positive anode and the negative cathode (and

window) the liberated electrons traverse a path somewhat as shown by the dotted lines in the figure, hitting the target at the focal spot. By varying the distance between the target and the window, the nature of the focal spot can be altered. The black spot at the top of Fig. 5.28 is a pinhole photograph of the focal spot for one arrange-



Courtesy Machlett Laboratories, Inc.

FIG. 5.28. *DD* represents the dome of the tube shown in Fig. 5.27, *CC* the cathode, *A* the water-cooled anode, *T* the target. The black spot at the top is a pinhole photograph of the focal spot.

ment. Anticipating later work on dosage, we may mention in passing that, with a tube of this kind operated at 60 kilovolts and a current of 100 ma, the manufacturers estimate that dosage rates of the order of 5 million roentgens per minute are obtained, over an area of 25 cm^2. By way of contrast, dosage values in Chaoul therapy are of the order of 100 roentgens per minute at a distance of some 5 cm from the target.

PROBLEMS AND QUESTIONS

1. What is the chief advantage of a line focus over a circular focal spot whose diameter is equal to the width of the line?
2. What methods are used to keep the target of an X-ray tube cool? Why is this desirable?
3. What are two special features of the metalix X-ray tube?
4. Describe very briefly three means which are utilized for keeping down the temperature of the target of a tube.
5. Discuss the relation of the size of the focal spot to (i) the power which may be supplied to a tube, (ii) the character of the radiographs taken, (iii) the question of treatment.
6. Why should a target of an X-ray tube be of high atomic weight?
7. When a hot filament tube is in good condition and 100,000 volts are applied across its terminals, the filament circuit not on, what should the milliampere meter read? If in such a case a glow were observed in the bulb, what conclusion would you draw?

8. What is meant by saturation tube current?

9. What effect has increasing the voltage across a hot filament tube on the tube current?

10. What connection is there between the focal spot and the input of an X-ray tube? Why may much larger X-ray tube currents be used for a short time than for long periods?

11. Describe as fully as you can the essential features of a good modern X-ray tube suitable for general diagnostic work.

12. What are the special features of the Chaoul therapy tube?

13. What is the special advantage of the rotating anode tube?

14. A slight increase in the voltage applied to a Coolidge tube in general does not change the tube current, whereas a slight change in the filament current may cause a marked change in the tube current. Explain the reason.

15. In a hot filament X-ray tube, explain (i) two methods of obtaining the equivalent of small focal spots with adequate power input; (ii) two methods of keeping the target cool.

16. Find the number of electrons which hit the target of a hot filament X-ray tube in 2 seconds, if the tube current is 20 ma.

17. Name and explain two ways of utilizing an increased amount of power in an X-ray tube without enlarging the effective size of the focal spot.

CHAPTER VI

RECTIFICATION, DIODE AND TRIODE VALVES

6.1. Self-rectifying Tubes. We have already emphasized that electrons leave a hot filament only when it is negative. Hence, if a tube such as the Universal Coolidge is placed directly across the high tension terminals of a transformer, current ordinarily passes only when the end of the secondary of the transformer which is attached

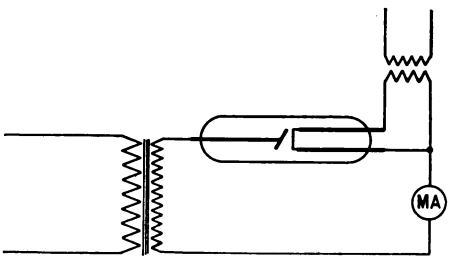


FIG. 6.1. An X-ray tube acting as its own rectifier.

to the anode, is positive. In the next half-cycle, when this end is negative, no current passes. Provided certain precautions are observed, therefore, a tube can act as its own rectifier, and so be used with the simple arrangement shown in Fig. 6.1. This is known as *self-rectification.* In Fig. 6.2. graph (*a*) represents the theoretical wave-form of the voltage applied to the tube, and (*b*) shows the theoretical* corresponding tube current. Note that it is intermittent but unidirectional.

In actual practice, in the great majority of cases, it does not do to let a tube act as its own rectifier. As we have already pointed out more than once, the focal spot on the target may become very hot. In the Universal tube, the whole anode sometimes becomes white hot. Now any metal emits thermionic electrons at high temperatures, hence, if an alternating high tension potential is applied to the tube, there is always the danger that, during the half-cycle when the anode

* By means of oscillographs the actual form of the curve can be obtained. Although it departs somewhat from the smooth type of curve shown in Fig. 6.2, the form of the current graph obtained by the oscillograph shows clearly the suppression of each half-cycle.

is negative, it will emit electrons due to a high temperature. Such an emission is disastrous to the tube. In addition to causing the libera-

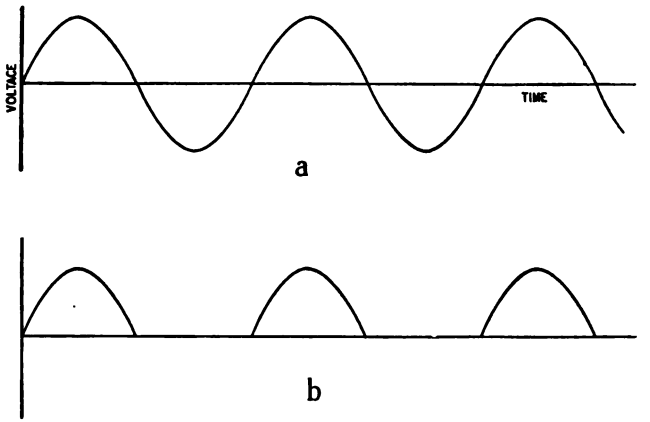


FIG. 6.2. In self-rectification, or half-wave, tube current flows only in alternate half-cycles.

tion of unwanted X-rays from places where these electrons strike, this beam from a hot anode may destroy the tube by the damage it does on impact. More often than not, therefore, hot filament tubes are operated on voltage which has been rectified, and invariably the rectifiers used are of the valve type.

The student should realize that the voltage across a tube during the half-cycle when current is not flowing, that is the *inverse voltage*, is higher than in the active half-cycle. (Try problem 16 at end of this chapter.)

6.2. Valve Rectifiers. As long ago as 1915 Dr. Saul Dushman, of the U.S. General Electric Research Laboratory, designed a rectifying valve for use in X-ray circuits, to which the name *kenotron* was

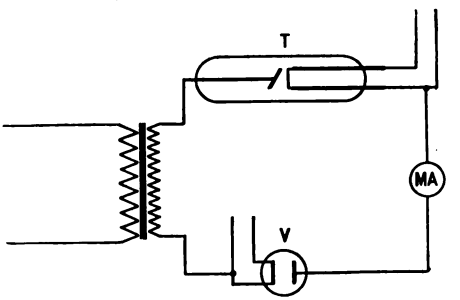


FIG. 6.3. Half-wave rectification by means of a single valve V in series with the tube T.

given. The simple arrangement utilizing a rectifying valve is shown in Fig. 6.3, where a single valve V is in series with the secondary of the high tension transformer and the tube T. It is well to note that, in order to avoid confusion, in all our diagrams we represent a valve by a circular diagram and an X-ray tube by a cylindrical one. Actually they may both be cylindrical in shape.

Although in one sense a rectifying valve and a hot filament X-ray tube are essentially the same, each with an anode and a hot filament cathode and each permitting the flow of electrons only when the filament is hot and when it is negative, nevertheless there are important differences. A tube is primarily for the production of X-rays,

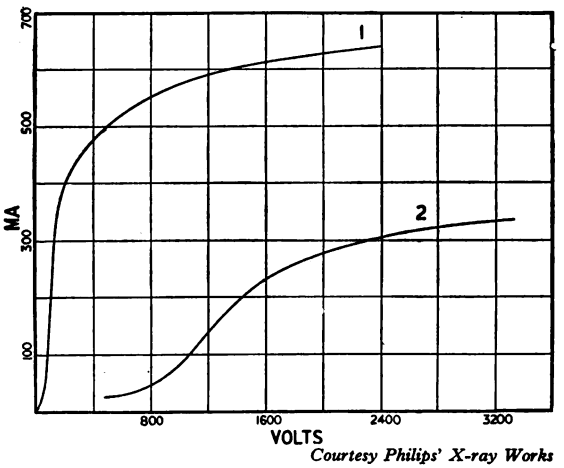


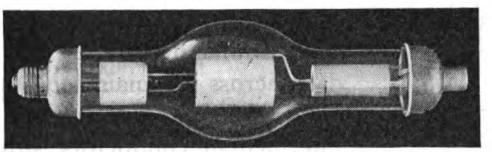
FIG. 6.4. Characteristic curves for two rectifying valves, 1 metalix, 2 glass.

whereas in a good valve, X-rays must *not* be generated. To avoid their production, the electrons must not be allowed to cross the valve at high speed, or, in other words, the voltage drop across the valve must be small. This is also desirable, because the greater the voltage drop across a valve placed as in Fig. 6.3, the less the voltage available for the tube.

In a good valve, then, the aim is to pass a high current at a low voltage. To insure this the valve must be so designed that the current through it is considerably below the saturation value. In section 5.8, the meaning of saturation current for an X-ray tube was explained, use being made of the graphs of Fig. 5.13. Because of the fundamental similarity between a tube and a (vacuum) valve, the

same type of graphs apply to a valve. In fact, Fig. 6.4, taken from literature of the Philips' Metalix Company, shows two similar graphs for two different types of rectifying valves. A glance at graph 1 will show that the valve to which this applies will pass a current of 300 ma when the voltage across it is less than 200 volts, a very small amount compared with tube voltages.

6.3. Types of Valves. The original kenotron and the kind of valve first put on the market by the Philips' X-ray Works were simple diode tubes, consisting essentially of the filament (and associated cathode) and the anode, in a highly exhausted glass container. In



Courtesy General Electric X-ray Corporation

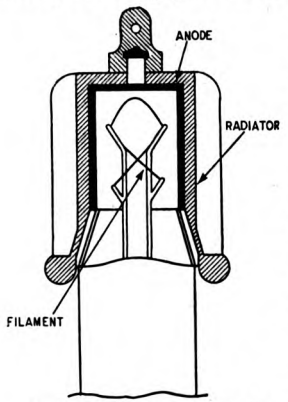
FIG. 6.5. A kenotron, (rectifying valve) with cylindrical anode surrounding a spiral filament.

some respects this arrangement proved unsatisfactory because with an unprotected filament, a negative charge collects on the inner surface of the glass walls, and this makes the valve erratic in its behaviour. To quote from General Electric literature: " this charge (the charging of the walls) produces a grid action which under variable circuit conditions may produce a voltage drop as high as 10,000 to 20,000 volts."

To overcome this defect, different devices have been used. For example, the U.S. General Electric now use " a cylindrical anode with a spiral filament inside ". Since the filament is thus surrounded, no negative charge accumulates on the glass container as all the electrons are caught by the anode. Figure 6.5 is a photograph of a kenotron of this type.

The Philips' Metalix Company have overcome the difficulty by making one end of the valve a metal cylindrical cap, which fulfils the double function of forming part of the container and acting as the anode. This anode " incloses the filament in all directions except in that of the insulating stem which supports the filament ". The general arrangement is shown in Fig. 6.6. In Fig. 6.4, curve 1 applies to a metalix valve of this sort, curve 2 to one with a glass envelope, the filament current in each case being the same. The marked superiority of the metalix valve is obvious.

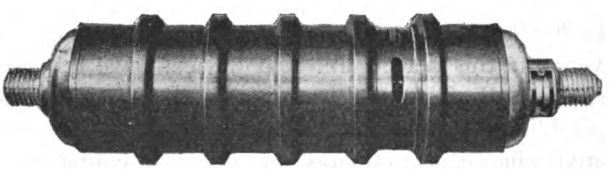
Figure 6.7 shows the external appearance of a valve of a different kind, recently put on the market by the Philips' Company. In this type residual gas is left in the valve and use is made of cumulative ionization by collision. Just as in the high vacuum type, electrons are emitted from the filament (of the dull emitter type) when it is negative, but the current is no longer a pure electron stream, for the gas is ionized by the colliding electrons. On the reverse half-cycle, when the filament is positive there is no electron emission and no ionization. In this type the manufacturer states that "the voltage drop across it remains constant at a figure of the order of 50 volts" and that "hollow intermediate conductors, situated at intervals along the interior of the discharge tube are interconnected by condensers which encircle the unit and perform the function of distributing the potential by equal stages along the length of the valve". Currents as high as 1,000 ma are possible with this kind of valve.



Courtesy Philips' X-ray Works

FIG. 6.6. Diagram of a rectifying valve with metal anode surrounding the filament.

6.4. Half-wave Rectification. Attention has already been directed to Fig. 6.1, the simple self-rectified circuit, and to Fig. 6.3, where a single rectifying valve in series with the tube gives rectification and added protection. To each of these circuits Fig. 6.2 is applicable. With the arrangement shown in Fig. 6.3, however, it is possible to use greater amounts of power than if the tube were its own rectifier. This figure illustrates the simplest case of *half-wave rectification.*



Courtesy Philips' X-ray Works

FIG. 6.7. A rectifying valve which will carry currents as high as 1,000 ma.

6.5. Full-wave Rectification. Figures 6.8*a* and 6.8*b* illustrate a type of rectified circuit in common use, the so-called Graetz circuit. In Fig. 6.8*a* the arrows indicate the direction of the current during

the half-cycle when the end *A* of the secondary of the high-tension transformer is positive, and the end *B* negative. Figure 6.8*b* applies to the alternate half-cycles when *A* is negative and *B* positive. If the

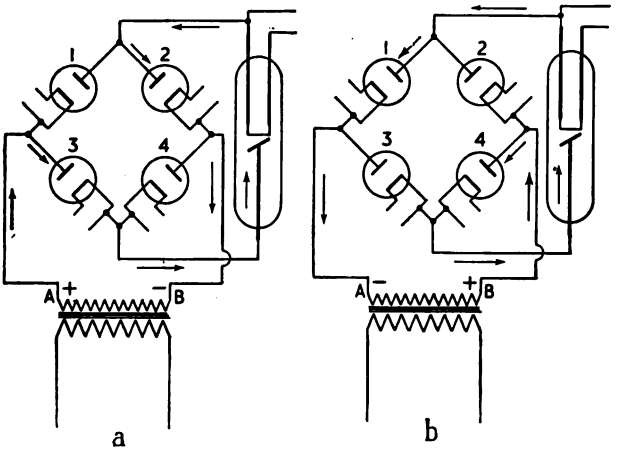


FIG. 6.8. The Graetz circuit for full-wave rectification.

student will remember that current will traverse a valve only when the filament is negative, he should have no difficulty in showing that in Fig. 6.8*a*, valves 1 and 4 are not in use, or in Fig. 6.9*b*, valves 2 and 3, but that in each case current passes through the X-ray tube.

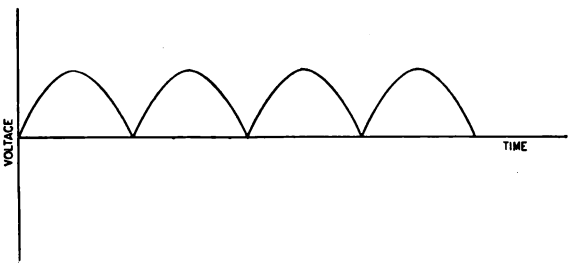


FIG. 6.9. In full-wave rectification there is tube current every half-cycle.

With this arrangement, therefore, use is made of each half-cycle, the theoretical form of the current being as shown in Fig. 6.9.

Full-wave rectification may also be obtained by the use of the two valve circuit shown in Fig. 6.10.

6.6. Tube Rating and Type of Rectification. In Fig. 5.23 an example of a rating chart for a certain tube was given. Now, as a matter of fact, the graphs in this chart were only applicable when this

tube was operated on full-wave equipment, and, in the manufacturer's literature, two other charts were given for the same tube, one applicable to half-wave, the other to self-rectified equipment. In explaining why a different chart is needed for each type of equipment, it is instructive to look at a concrete case.

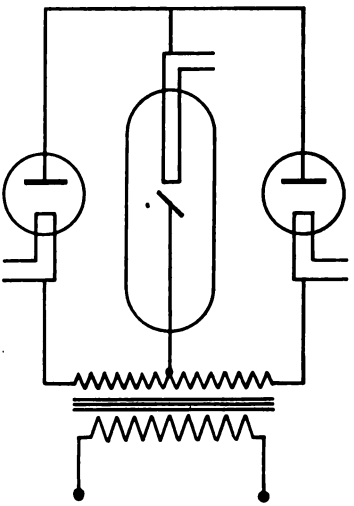


FIG. 6.10. Full-wave rectification using two valves.

From the three charts supplied by the General Electric Company for their RB 1-4 tubes (with small focal spot) one finds out that, when one of these tubes is operated on 60,000 volts, with 20 ma current, the maximum permissible exposure time is 40 seconds for full-wave equipment, 15 seconds for half-wave, and 2 seconds for self-rectification. It is not difficult to see why with self-rectified use the same amount of power can be used for a much shorter time than with half-wave rectification. Without the valve, there is danger of inverse current through the tube, once the focal spot reaches a certain temperature. The presence of the valve, however, does not allow any current to flow even when the focal spot reaches this or a higher temperature.

It is not so easy to see why the permissible time for operation on full-wave is longer than on half-wave. To understand the reason the

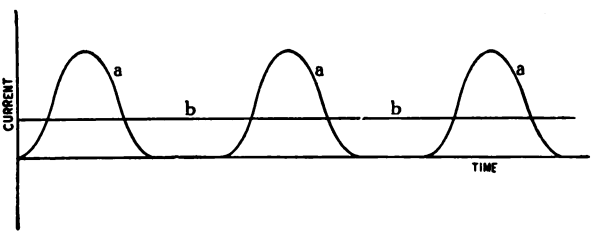


FIG. 6.11. The line *b* represents the steady current recorded by a milliammeter in half-wave rectification.

student must be clear about the difference between the current recorded by the milliammeter in the tube circuit, and the actual value it may attain in a half-cycle. Consider half-wave rectification, where the current is completely suppressed every alternate half-cycle,

and where an oscillograph shows the intermittent, pulsating nature of the current, somewhat as in Fig. 6.11, curve *a*. The current changes, however, are much too rapid (remember that the time of a half-cycle is 1/120 second for a 60 cycle per second supply) to be registered by the moving parts of a milliammeter, and this instrument records only a steady mean, of magnitude considerably less than the highest values reached every alternate cycle. In Fig. 6.11, the line *b* represents the steady mean current recorded by the milliammeter. It follows that, if a milliammeter records, say 20 ma, the current through the valve and the X-ray tube may actually attain a value several times 20 ma —at least three times as great, according to information taken from Philips' literature.

Now consider full-wave rectification, as depicted in Fig. 6.12. In this case, because current passes through the tube *every* half-cycle the mean milliamperage is much nearer the peak value, this being only about one and a half times as great as the mean. Thus for a milliammeter reading of 20 ma, the actual tube and valve current

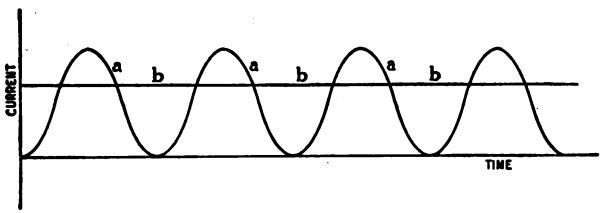


FIG. 6.12. The line *b* represents the steady current recorded by a milliammeter in full wave rectification.

may be as high as 60 ma for half-wave rectification, and about 30 ma for full-wave. Hence, although the total power supplied a tube in each case may be the same (an average of 20 ma at a peak voltage of 60,000), in the case of half-wave equipment, it is given in " doses " which are much more intense, but half as frequent as in the case of full-wave. Since heat generated at the focal spot takes an appreciable time to be dissipated, this means that higher focal temperatures are reached with half-wave than with full-wave, with consequent shorter permission times of tube operation.

6.7. The Use of Condensers with Valves. Consider a circuit arranged as in Fig. 6.13, where *C* represents a condenser of fairly high capacity and one capable of withstanding X-ray potentials. During the half-cycle when *A* is positive and *B* negative, as in Fig. 6.13*a*, current can flow both through the X-ray tube and into the condenser,

charging it as indicated in the diagram, the potential difference across the condenser being the same as across the tube. During the next half-cycle, as represented in Fig. 6.13*b*, no current can flow from

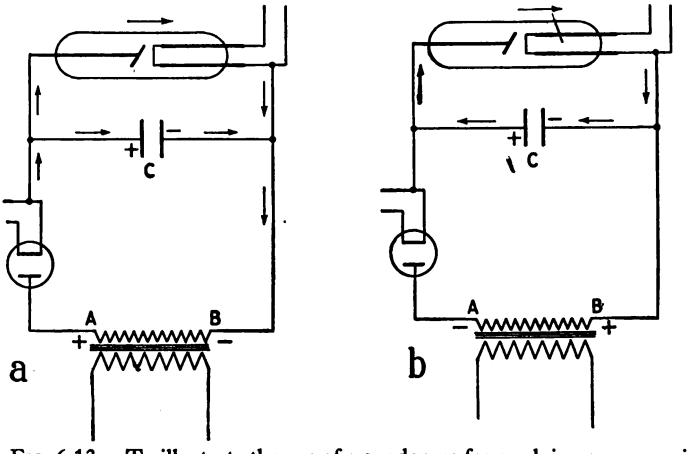


FIG. 6.13. To illustrate the use of a condenser for applying an approximately constant potential across an X-ray tube.

the transformer because the negative end of its secondary is attached to the anode side of the rectifying valve. During this half-cycle, however, the condenser can discharge through the tube, with a drop in voltage which is small compared with the maximum potential to which it was charged. To understand why the voltage drop is small, let us make an estimate using actual numerical values.

Suppose the average tube current during this discharge of the condenser is 20 ma and that the capacity of the condenser is 0·1 microfarad. Then during a half-cycle of 1/120 of a second, the quantity of electricity which leaves the condenser

$$= \frac{20}{1{,}000} \times \frac{1}{120} \text{ ampere-second or coulomb}$$

$$= \frac{1}{6{,}000} \text{ coulomb.}$$

But, since the capacity of the condenser is $\frac{1}{10}$ mf or $\frac{1}{10} \times 10^{-6}$ farad, if V is the voltage drop, the quantity of electricity which leaves the condenser also

$$= \frac{1}{10} \times 10^{-6} \times V \text{ coulomb.}$$

$$\therefore \quad 10^{-7}V = \frac{1}{6{,}000}$$

or $$V = 1{,}667 \text{ volts.}$$

Compared with the peak voltage developed in the secondary of the transformer, this is slight.

With the above arrangement, then, the voltage applied to the tube will remain moderately steady, somewhat as represented in Fig. 6.14, a copy of a diagram published by Watson and Sons (Electro-medical) Limited, London.

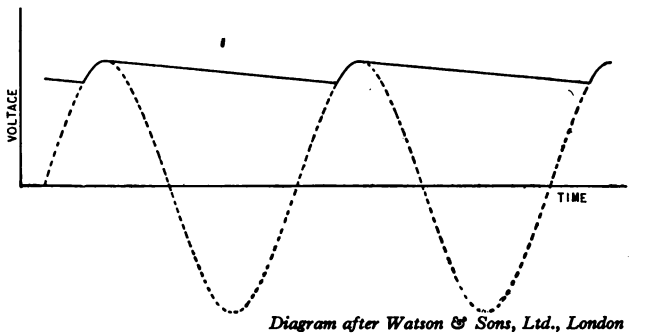


FIG. 6.14. With the arrangement shown in Fig. 6.13, the drop in tube voltage is slight.

6.8. The Greinacher Circuit. In the above arrangement we have noted that during every alternate half-cycle the transformer does not supply any power to the circuit. Actually condensers and valves are used in less simple arrangements. The Greinacher circuit shown in Fig. 6.15 is an example of one arrangement which has been widely used. In it, by the use of two condensers and two valves, (1) the transformer is utilized every half-cycle; (2) the voltage drop across the tube is slight; and (3) approximately twice the transformer voltage is applied to the tube.

By reference to Fig. 6.15, it will be seen that, during the half-cycle when A is positive and B negative, condenser C_1 is charged to the maximum voltage developed in the secondary of the transformer, whereas on the alternate half-cycle, when A is negative and B positive, C_2 is similarly charged. Once the condensers are charged, *each* of them can send a current through the X-ray tube, since in the circuit 1 2 4 3 the condensers and the tube are in series. Moreover, just as explained in the previous section, the voltage drop in each half-cycle will be slight. Again, since each condenser is charged to

the transformer voltage and the two are in series with the tube, the tube voltage is approximately twice that of the transformer.

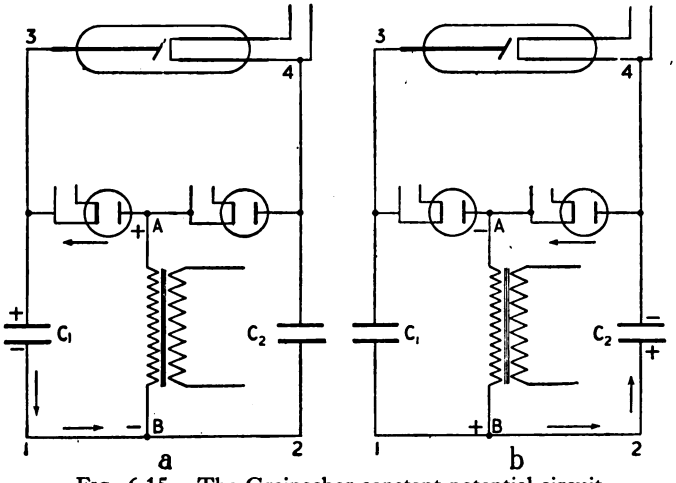


FIG. 6.15. The Greinacher constant potential circuit.

An alternative Greinacher circuit may be made by interchanging the positions of the valves and the condensers in Fig. 6.15.

6.9. The Villard Circuit. This circuit, also widely used, is

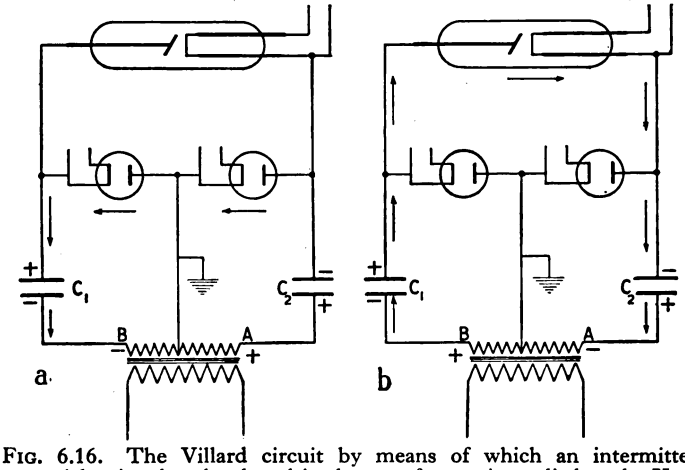


FIG. 6.16. The Villard circuit by means of which an intermittent potential twice that developed in the transformer is applied to the X-ray tube.

illustrated by Figs. 6.16 and 6.17. By means of it double the transformer voltage is applied to the tube, but the tube current is not continuous as in the Greinacher arrangement. As will be seen by a

study of Fig. 6.16*a*, during the half-cycle when A is positive and B negative, current can pass through the *valves*, the condensers consequently being charged as indicated. On the reverse half-cycle as shown in Fig. 6.16*b*, current cannot pass through the valves, but each condenser can discharge through the tube, while at the same time, the voltage developed in the secondary of the transformer is also in the right direction to cause a tube current. Since the two condensers, the secondary of the transformer, and the tube are all in series, as can be seen in Fig. 6.16*b* or Fig. 6.17, the resultant voltage causing a tube current is equal to the sum of the transformer voltage plus that across C_1 plus that across C_2.

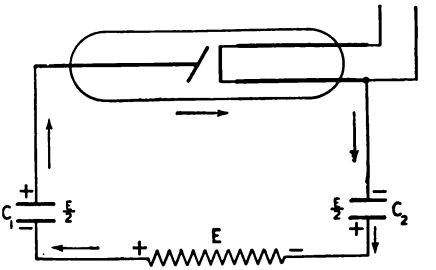


FIG. 6.17. A portion of the Villard circuit illustrating the half-cycle in which both condensers and secondary of transformer cause a tube current.

Now, in a simple circuit such as shown in Fig. 6.18, where two condensers of equal capacity are joined in series with a battery, the voltage drop across each condenser is just one half the e.m.f. of the battery. In Fig. 6.16*a*, when the current is passing through the two valves with the condensers in series, we have essentially the same circuit, the secondary of the transformer replacing the battery. The condensers, therefore, are each charged to a voltage of $V/2$, where V is the effective voltage developed by the transformer. Hence, in Fig. 6.16*b*, the effective voltage applied to the tube is $V+V/2+V/2$ or $2V$. Figure 6.19, taken from valve literature by the Philips' Metalix Company, is an actual oscillographic record showing the changes in tube current in a Villard circuit.

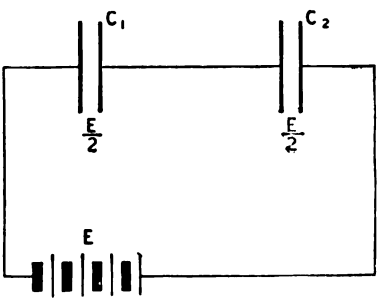
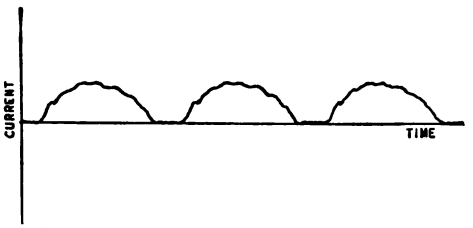


FIG. 6.18. When two condensers are in series with a battery of e.m.f. E volts, the potential difference across each condenser is $E/2$ volts.

It will be noted that two valves are used in the above arrangement. Actually this is not necessary and in the original circuit, only one was used. It was found, however, that by using two valves, with grounding and the balanced arrangement of Fig. 6.16, more satisfactory operation was obtained,

and, moreover, the circuit was more suitable for use with shockproof tubes.

We have by no means exhausted the types of rectifying circuits, but, as the aim of this book is to explain principles rather than give



Courtesy Phillips Metalix

FIG. 6.19. An actual oscillogram of tube current when ordinary metalix tube is operated by Villard circuit.

exhaustive technical details, it is considered that enough has been given to make clear the fundamental ideas. So far, too, we have confined our attention to arrangements and devices used for ordinary diagnostic and moderate voltage therapy circuits. We have still to discuss ultra-high voltage arrangements. This is done in Chapter XIII.

6.10. The Triode Vacuum Tube. To understand the action of this type of tube, it is necessary to amplify the work previously given about the passage of electrons across an evacuated tube. The graphs given in Fig. 5.13 and Fig. 6.4 show the way in which the current across a hot filament X-ray tube or rectifying vacuum tube varies with the applied voltage, at constant filament temperature. This type of curve applies to any *diode* vacuum tube, that is, a highly exhausted tube with filament and anode.

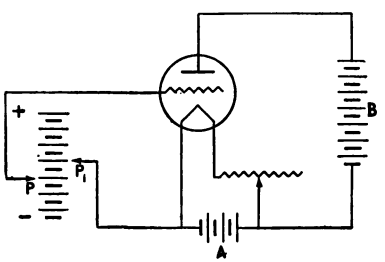


FIG. 6.20. Circuit for examining the effect of grid potential on the plate current in a triode vacuum tube.

In the *triode* vacuum tube, in addition to the filament which liberates electrons when heated, and the plate or anode, a *grid* constitutes a third element. In the tube diagram appearing in Fig. 6.20 the grid is represented by the central wavy line, but actually it is a spiral of fine wire, or a wire mesh, in close proximity to the filament. The anode or plate more or less surrounds the grid. To demonstrate

the function of the grid, a circuit such as that illustrated in Fig. 6.20 may be used. With this arrangement by varying the position of the contact P, the potential of the grid with respect to P_1 and hence with respect to the filament can be made either positive or negative. It is possible then to maintain the plate at a constant potential (by means of the battery B) and to examine the variation of the current to the plate when the grid potential is given a series of values, both positive and negative. The graph of Fig. 6.21 shows the general nature of the result obtained when such an experiment is carried out. Note the following :

(1) For negative potentials greater than OA, there is no plate current. The actual value of OA is considerably less than the plate potential. For example, in a tube examined in a laboratory class by a student, for a plate potential of $+70$ volts, OA was -22 volts.

(2) The main portion of the curve is almost linear, in some tubes exactly so, in others somewhat curved. This is the important part of the curve, because normally the potential of the grid, or its *bias*, is such that the tube is operated on this portion of the curve.

(3) Saturation can be obtained, as in the diode, but it requires a fairly high positive grid voltage, and in using a triode as an oscillator (or a detector) it must be avoided. In making characteristic curves similar to that of Fig. 6.21, it is really not necessary to extend the graph to this stage.

(4) By using a series of different plate voltages, a corresponding series of characteristic curves can be obtained. From an examination of these curves, the very important fact emerges that *a small change in grid potential may bring about the same change in plate current as a much larger change in plate voltage.* For example, in the case of the tube mentioned in (1) above, the student found that, with constant grid potential, a change of 30 volts in plate potential caused a change of 21 ma in the plate current, but, at constant plate potential, a change of only 8·25 volts on the grid brought about the same change in plate current. In other words, because of its proximity to the filament, the grid exercises a powerful control over the plate current. Its nearness to the filament makes it extremely efficient in attracting or repelling electrons, whereas

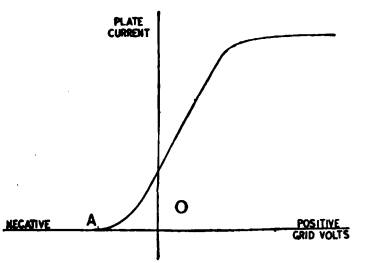


FIG. 6.21. Graph showing the variation of plate current in a triode vacuum tube with variable grid and constant plate potentials.

its open mesh nature allows most of the electrons to pass through and reach the plate.

In electronic circuits triode tubes are of the greatest importance. A brief reference is made to the following applications of the triode.

6.11. Triode as Detector. Because of the almost negligible inertia of electrons, grid control makes it possible to detect rapidly changing incoming electrical signals and hence to use the triode as a receiving device for radio waves. Waves picked up by an antenna to which the grid is attached cause small periodic changes in its potential. More intense changes of the same frequency then occur in the plate circuit. The input signals have been both detected and *amplified.*

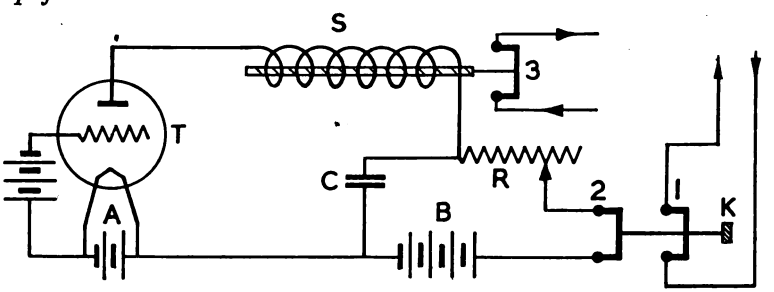


FIG. 6.22. Simplified circuit for a triode timer. (Adapted by kind permission from diagram in *X-rays, their Origin, Dosage and Practical Application,* by W. E. Schall, 5th Edition (1940).)

6.12. Triode as Amplifier. To make the subject of amplification quantitative, the term *amplification factor* (symbol μ) of a tube is adopted. By definition

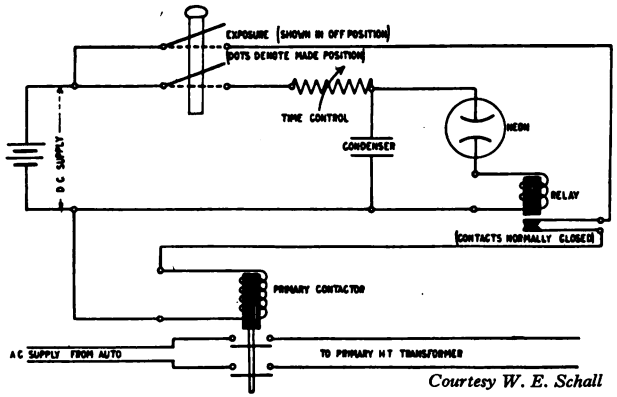
$$\mu = \frac{\text{change in plate potential producing a small change in plate current}}{\text{change in grid potential producing the same change in plate current}}.$$

For example, the tube for which data has been given in section 6.10 has a value of μ equal to $\frac{30}{8{\cdot}25}$ or 2·5. Values of μ, which vary with the type of tube, cover a wide range.

By using a succession of tubes in such a way that the amplified signals in the plate circuit of the first tube become the input for the second, and so on for the whole series, overall amplifications of the order of millions can be obtained. Such an *amplifier* is a common unit in many electronic devices.

6.13. Triode as Timer. The use of a triode for cutting off the high tension voltage applied to an X-ray tube after a pre-determined

time can be understood by reference to Fig. 6.22, which has been adapted, by the kind permission of Mr. W. E. Schall, from an illustration in his book *X-rays, their Origin, Dosage and Practical Application*, 5th Edition, 1940. In the arrangement shown in this



Courtesy W. E. Schall

FIG. 6.23. A timer using a neon lamp instead of a triode.

diagram the grid of the triode T is set with a negative bias so that there will be no plate current until the positive plate voltage reaches a certain value. The plate circuit includes a solenoidal coil S with a moveable iron core (attached to the switch 3), a condenser C in parallel with the tube and the coil S, and an adjustable resistance R. When switch 2 is closed by pressing the knob K, the positive terminal of the B battery is connected to the plate. Simultaneously the closing of switch 1 completes the high tension circuit (not shown in the diagram) and current begins to flow in the X-ray tube. But, because the condenser C is being charged after the closing of switch 2, the potential of the plate *gradually* rises and current does not flow in the plate circuit through S until the plate potential is high enough to counteract the negative bias on the grid, that is, until an appreciable time interval after the closing of 2. The length of this interval can be altered by varying the value of the resistance R. With the onset of the plate current, the iron core moves into the solenoid and closes switch 3. By a control circuit not shown, the closing of this switch cuts off the high tension.

Fig. 6.23, kindly given the author by Mr. W. E. Schall, is an improved form of timer based on the same general principles as those used in Fig. 6.22. The essential difference is that a neon lamp replaces the triode. This lamp does not conduct or " strike " until a sufficiently high d.c. voltage is applied to its terminals.

6.14. Triode as Oscillator. Suppose a circuit is arranged as in Fig. 6.24. It will be noticed that the loop *RLC* contains an inductance and a capacity, and consequently, if the resistance is low, has a natural frequency of electrical oscillations given by $f = \frac{1}{2\pi\sqrt{CL}}$.

If for any reason a movement of charges is started in such a circuit and, in consequence, a small charge is given to the condenser, this loop should oscillate with this frequency. If such a circuit were an independent, separate unit, and not part of an arrangement like Fig. 6.24, these oscillations would be very feeble and would rapidly die out. In Fig. 6.24, however, one side of the condenser of this oscillating circuit is joined to the grid of a triode. If, therefore, oscillations are started in the loop *RLC* (and even the closing of a switch can cause an initial electrical disturbance), the potential of the grid will change with the frequency of the oscillations. As we have seen, these rapid changes in grid potential cause equally rapid changes in the plate circuit and therefore also in the coil L_1 inserted in the circuit.

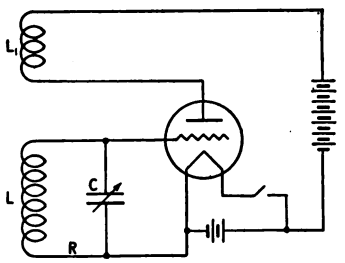


FIG. 6.24. Circuit to illustrate the principle of retroaction and the use of a tube in generating high frequency currents.

If, now, the coil L_1 is placed near the coil L, that is, is *coupled* with it, electromotive forces of the same frequency as the frequency of the plate current changes are induced in L. These electromotive forces (if the coils are suitably wound with respect to each other) reinforce the oscillations originally started in the circuit *RLC*. The reinforced oscillations cause greater potential changes in the grid, hence changes of greater magnitude in the plate current, hence induced electromotive forces of still greater intensity in the original oscillating circuit. There is, therefore, a cumulative effect which results in the maintenance of continuous oscillations. " It is possible to increase the effect of this induction sufficiently to make full compensation for ohmic and other losses in the circuit so

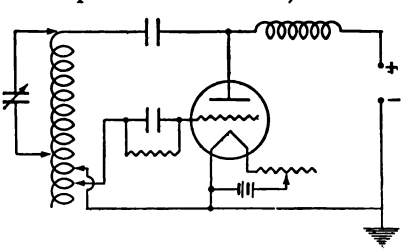


FIG. 6.25. Connections for the Hartley oscillator.

that the system behaves as if it possessed zero resistance, and an oscillation once started in it, persists." (Appleton.)

By this principle of retroaction *continuous* undamped oscillations are maintained. In actual practice there are many different circuits employing this principle in one way or another. Figure 6.25, for example, shows the connections for a Hartley oscillating circuit, one which has been extensively used.

6.15. The Generation of Electric Waves. The rapidly changing currents in an oscillator radiate electric waves in the surrounding space. Depending on the oscillator, waves as short as a fraction of a millimetre and as long as several miles have been generated in this way. In radio almost the whole range is utilized in some way or other. On the dial of a common type of radio, one finds three bands, the standard broadcasting region with wave lengths ranging from 200 metres or less to nearly 600 metres; a medium region ranging from approximately 45 metres to nearly 200 metres; and the short wave region with wave lengths extending from about 12 metres to 45 or more. In radar, wave lengths a few centimetres or even millimetres in length are used.

The particular kind of electric waves used is often described by giving frequency rather than wave length, the two being connected by the fundamental wave equation $v = f\lambda$. Thus, since the velocity of all electromagnetic waves is 3×10^8 metres per second, a wave length of 300 metres corresponds to a frequency of $\frac{3 \times 10^8}{300}$, or 10^6, or 1 million, or 1 megacycle per second.

The name electric waves is restricted to those generated by oscillations in an electric circuit. They are a particular kind of electromagnetic waves and are of the same fundamental nature as many other types of radiation, such as infra-red, ultra-violet and visible light, X-rays and gamma rays from radioactive materials. Differing widely in their properties because of differing wave lengths, all these radiations are periodic electric and magnetic disturbances which travel in free space at the same velocity. A glance at Table X* will show the enormous range of wavelengths. Those with which we shall be concerned in this book are so short that the following special units of length are used: (*a*) the *angstrom*, which to a high order of accuracy $= 10^{-8}$ cm, and (*b*) the so-called *X* unit, which within 0·2 per cent $= 10^{-11}$ cm. For practical purposes, 1 angstrom = 1,000 *X* units.

* The limiting values given in this table are only approximate.

TABLE X—RANGE OF ELECTROMAGNETIC WAVE LENGTHS

Kind	Longest	Shortest
Electric - - -	20 + miles	0·22 mm
Infra-red, far - -	0·4 mm	15,000 angstroms
Infra-red, near - -	15,000 angstroms	7,700 angstroms
Visible - - -	7,700 angstroms	4,000 angstroms
Ultra-violet, near -	3,900 angstroms	2,900 angstroms
Ultra-violet, far - -	2,900 angstroms	1,800 angstroms
Ultra-violet, extreme -	1,800 angstroms	40 angstroms
X-rays - - -	500 angstroms	0·05 angstrom
Grenz X-rays - -	5 angstroms	1 angstrom
Diagnostic X-rays -	0·3 angstrom	0·1 angstrom
Therapeutic X-rays -	0·1 angstrom	0·001 angstrom
Gamma rays - -	0·3 angstrom	0·006 angstrom

PROBLEMS AND QUESTIONS

1. Make a fully labelled diagram of the electrical connections in an X-ray tube outfit which utilizes the following features: (i) autotransformer control; (ii) a four valve rectifying arrangement (the Graetz circuit); (iii) a hot filament X-ray tube; (iv) a filament current ammeter (for X-ray tube); and (v) a milliammeter in tube circuit. Indicate by arrows the current path in the tube circuit during one half-cycle.

2. Explain, with the aid of simple diagrams, the difference between self-rectification, half-wave rectification, and full-wave rectification.

3. Why is a rectifier desirable in operating a standard universal Coolidge tube but not necessary for the radiator Coolidge tube?

4. Under what circumstances can a very high vacuum be made conducting? Describe the mode of conduction.

5. With the aid of diagrams describe and explain a rectifying circuit for an alternating high tension voltage; (i) using every half-cycle, by means of a single valve and a condenser; and (ii) using alternate half-cycles, but (approximately) doubling the transformer voltage.

6. A hot filament tube, whose filament is heated by a step-down transformer, is operated by a high tension transformer, with autotransformer control, and with a Villard rectifying arrangement. Make a complete diagram of the electrical system.

7. A condenser of a capacitance 1/10 microfarad is charged to 200,000 volts. It then maintains an average current of 10 ma through an X-ray tube for 1/100 second. Find the voltage across the condenser at the end of this time. *Ans.* 199,000 volts.

8. With the aid of two diagrams, one for each half-cycle, show how a condenser may be combined with a single rectifying valve and transformer to maintain an approximately steady voltage across an X-ray tube.

9. Make a diagram showing the essential connections when an X-ray tube is operated by a transformer rectified by a Greinacher circuit.

10. A hot-filament X-ray tube is operated with a full-wave rectifying arrangement. The P.D. across the primary of the high tension transformer

is controlled by a rheostat and all hot filaments are heated by step-down transformers. Make a careful diagram showing all essential circuits.

11. Make a diagram of the circuit you would use to obtain the characteristic curve (that is, tube current against voltage) for a diode valve or a rectifying valve. Indicate the nature of the curve you would obtain.

12. Make a complete diagram showing the essentials of an X-ray high tension circuit with autotransformer control of voltage and a *full-wave* rectifying circuit.

13. Make a labelled diagram showing the essential connections, when a hot filament X-ray tube is operated, with autotransformer control of voltage and the Greinacher constant potential circuit. Show complete filament and primary circuits.

14. High frequency oscillations are set up in a circuit of very low resistance containing a condenser of capacity 0·001 microfarad and an inductance of 0·00002 henry. Calculate the frequency of the currents. *Ans.* $1{\cdot}12 \times 10^6$.

15. If electric waves are radiated from the circuit described in question 14, calculate the wave length of the waves. *Ans.* 268 metres.

16. A high tension transformer of turns ratio 350 : 1 has 200 volts applied to its primary. A self-rectifying tube is connected to the secondary. Find the peak value of the inverse voltage across the tube.

17. (*a*) Comment on the following ratings of two diagnostic tubes, both with a 1×1 mm focal spot and both running at 80 kVp. Stationary anode : 15 ma for 1 sec ; 5 ma continuous. Rotating anode : 150 ma for 1 sec ; 5 ma continuous.

(*b*) What would you expect the ratings to be if the focal spots on the same tubes were 2×2 mm?

(*c*) The above figures correspond to full-wave rectification. Would they be the same or different on half-wave with valve and on self-rectified operation?

18. Which part of the characteristic curve of a diode is used in the operation of : (*a*) a rectifying valve ; (*b*) an X-ray tube?

19. When the 100 kVp output of a transformer is applied to an X-ray tube through 2 valves, the peak tube current is 150 ma. If under these conditions the impedance of each valve is 10,000 ohms, find the peak voltage across the tube. *Ans.* 97 kVp.

20. An X-ray transformer takes a current of 30 amperes from 230 volt mains, at a power factor of 0·9, when supplying a tube current of 60 ma at a potential difference across the tube of 75 kVp. What fraction of the total input is used to operate the tube? *Ans.* 0·57. (*N.B.*—r.m.s. current = 1·11 mean current.)

21. An X-ray transformer takes a current of 50 amperes from 250 volt mains, at a power factor of 0·8, when supplying a tube current of 100 ma at a tube potential difference of 80 kVp for an exposure of 50 ma. (*a*) Find the cost of supplying power for 120 exposures at 2d per unit. (*b*) If the efficiency of X-ray production is 1 per cent, find the heat dissipated at the target.

CHAPTER VII

GENERAL PROPERTIES OF X-RAYS

In section 3.10 it was pointed out that a beam of X-rays radiates from the focal spot of an X-ray tube. In this chapter we shall discuss some of the important properties of such a beam.

7.1. Photographic Effect. X-rays affect a photographic plate or film, or sensitized paper in much the same way as ordinary light. The speeds of different photographic emulsions vary, and, for the same plate, the speed varies with the kind of rays used. Details relating to X-ray photography will be found in Chapter IX.

7.2. Fluorescent Effect. X-rays excite fluorescence in certain substances on which they fall. By fluorescence we mean the emission of visible light which continues as long as the rays strike the substance. As it was the fluorescent property which led to the discovery of X-rays by Roentgen, it is of interest to quote a few sentences from a translation of a preliminary communication read by Roentgen, on Dec. 28, 1895, before the Physikalisch-medicinischen Gesellschaft of Wurzburg. " If the electric discharge from a large Ruhmkorff coil is passed through a Hittorf vacuum tube, or through a sufficiently exhausted Lenard, Crookes, or similar tube, and if the tube is covered with a fairly close fitting envelope of thin black card, it will be found that a paper screen placed near the apparatus and covered with barium platinocyanide will become brightly luminous and fluorescent. It is immaterial whether the prepared side or the unprepared side is turned towards the apparatus. The fluorescence is still noticeable at a distance of two metres from the apparatus. It is easy to establish that the cause of the fluorescence proceeds from the discharge tube and from no other part of the electric circuit.

" The first remarkable feature about this phenomenon is that we have here an agent that can pass through a black card envelope which is impervious to the visible and ultra-violet rays of the sun or electric arc, and that this agent is capable of producing vivid fluorescence. The fluorescence of barium platinocyanide is not the only recognizable effect of the X-rays. Other bodies also fluoresce, as for instance the calcium compounds known as phosphor; also uranium glass, ordinary glass, calcspar, rocksalt, etc.

" Photographic dry plates are sensitive to X-rays, and this fact is

of special importance in many respects. It enables many phenomena to be recorded, thus making it easier to exclude deceptions, and whenever possible I have checked by means of a photographic exposure every more important visual observation on the fluorescent screen."

In radiology three applications of the fluorescent effect of X-rays are made: (1) in the use of a *fluorescent screen* for diagnostic purposes; and (2) in the use of *intensifying screens* for shortening exposures when radiographs are being made; and (3) in the *image intensifier*.

In fluoroscopy the radiologist observes visually the shadow pictures on a fluorescent screen when a patient is between the X-ray tube and the screen. Sometimes the fluorescent image is photographed to obtain a permanent record, this process being called *fluorography*. A good example of fluorography is found in the X-ray chest surveys of large groups of people in which photographs are taken as quickly as one per minute.

In standard photographic diagnosis or roentgenography exposure times are shortened by the use of intensifying screens. These screens, which are made of such substances as tungstate of calcium, are placed directly in contact with the sensitive emulsion on the photographic plate or film. Wherever the rays strike the screen, therefore, the bluish (fluorescent) light emitted (which is much more actinic than X-rays) acts on the emulsion and so shortens the exposure to a marked degree. A reduction as much as five- to tenfold is quite normal. Care must be taken to keep the screen clean, for particles of dust will absorb the visible fluorescent light and spot the plate. The exposure may be still further shortened by using films sensitized on both sides along with intensifying screens on each side of the film. " In actual use intensifying screens are mounted in rigid holders called cassettes, in order that perfect contact may be obtained between emulsion and screen." (Eastman Kodak Co.)

It is of interest to note that there are a number of fluorescent materials or *phosphors*, the choice of a suitable one depending on the purpose for which it is used. Thus, whereas calcium tungstate is good for photographic purposes, a zinc sulphide screen, which emits a green band of light in the spectral region to which the eye is most sensitive, is better for fluoroscopy.

There is a second type of intensifying screen based on an entirely different principle. In this method lead foil of thickness as small as 0·002 in. is placed against the emulsion, use being made of the

secondary electron emission generated by the photoelectric action of the X-ray beam on the lead. This method has advantages when it is desirable to use rays which are more penetrating than those ordinarily employed in medical radiography, or when gamma rays from radioactive sources are used.

The use of the fluorescent effect in the image intensifier is explained in section 7.11, where further details about fluoroscopy are given.

7.3. Chemical and Dehydrating Effects. X-rays produce a discolouration of certain alkaline salts, liberate iodine from a solution of iodoform in chloroform, and change the colour of certain substances such as barium platinocyanide.

7.4. Biological Effects. The burns which result from undue exposure to X-rays; the beneficial effects of the rays in curing certain skin diseases; the stunting of the growth of young animals; the production of injuries and of genetic changes in cells; the destruction of cells and the killing of eggs of the Drosophila fruit fly; the production of carcinogenesis and a possible germicidal action on bacteria—these are some of the many examples of this important property concerning which more will be stated later.

7.5. Ionization Effect. X-rays make the air through which they pass conducting, as may readily be shown by placing a charged electroscope almost anywhere near a tube. On sending a current through the tube it is at once observed that the leaf of the electroscope steadily falls until the whole charge has disappeared. The rays have ionized the air in the neighbourhood of the electroscope to an extent which is proportional to the rate at which the leaf falls. Should the experiment be repeated a number of times, each time placing the electroscope at a greater distance from the tube, it would be found that the leaf falls more slowly the further it is removed from the tube. This indicates that the ionization and so the intensity of the beam of X-rays at a local region is greater, the nearer the region is to the tube. (Sections 11.1, 11.2, 11.3.)

As the ionization property is the basis of the most accurate methods of estimating dosage when X-rays are used for treatment, the importance of this property cannot be too strongly emphasized. Later, details of suitable ionization chambers will be given; at this place, however, a simple form of electroscope which has been found useful may be noted (Fig. 7.1). The leaf is attached to the usual metal support but this, instead of ending in a knob outside the electroscope, is supported by means of the insulating bead of sulphur *S*.

The whole is enclosed in an earthed metal chamber with a window *W* covered with very thin metal foil through which X-rays may pass. The electroscope is charged by means of a movable rod *R* which passes through an insulating support to the outside of the box.

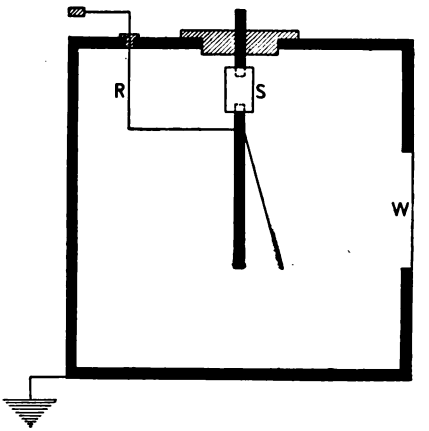


FIG. 7.1. A simple electroscope for rough ionization measurements.

7.6. Photoelectric Effect. When X-rays are absorbed by matter there is often a *photoelectric emission of electrons*. This important effect, which is closely connected with ionization, is discussed in detail in sections 10.4 and 10.7.

7.7. Penetrating Effect. There are few people nowadays who are not familiar with the fact that X-rays pass through fairly thick sheets of matter which we ordinarily call opaque. A piece of wood is almost as transparent to X-rays as window glass is to sunlight. But thin layers of any substance are more transparent than thick, and some substances are more opaque than others; herein lies the basis of the familiar X-ray pictures. Radiographs are just shadow pictures, wherein detail is visible because of the unequal degree to which different parts of the subject photographed absorb X-rays. There are in consequence corresponding differences in density on the plate or film. (See Chapter IX.) As the whole application of X-rays both for radiography and for treatment is bound up with the question of absorption of X-rays, the question of penetrating power will now be considered in detail.

It is first of all important to realize that the terms opacity, or opaqueness, or transparency, of a substance to X-rays are very indefinite. An experimental illustration will make the point clearer.

Before the window of a charged electroscope of the kind shown in Fig. 7.1 is hung a sheet of aluminium several millimetres thick. On placing a small gas X-ray tube (operated by an induction coil developing some 10,000 or 20,000 volts) a short distance away, with its target pointing towards the window of the electroscope, it is found that the leaf of the electroscope remains stationary or falls extremely slowly. On using a larger tube, however, operated by an X-ray transformer on some 50,000 volts, the leaf falls in a matter of a few seconds. The aluminium is opaque to the first beam of X-rays, but far from it to the second. In other words, X-rays from some tubes are more penetrating than from others.

Again, the same bulb when operated under different conditions emits rays which have different penetrating effects. Suppose a hot filament tube is used, with always the same milliamperage, but at a series of different voltages. Suppose, further, that for each voltage the distance of the tube from the electroscope is adjusted so that in each case the leaf falls at the same rate, when no absorbing sheet of metal is present. If now another set of readings is taken from each voltage, at corresponding distances, with an absorbing layer of metal interposed, it is found that the higher the voltage the more rapidly the leaf falls. The conclusion is obvious—the higher the voltage across a tube the more penetrating are the rays emitted.

There are, therefore, different kinds of X-rays which we may describe as *hard, medium, or soft*, according as they are very penetrating, moderately penetrating, or feebly penetrating. But the terms hard, medium, and soft, are much too elastic for the accurate measurement of so important a quantity as the penetrating power and we must seek some means of expressing degrees of hardness by definite numbers. In other words, we need a scale in terms of which the *quality* of a beam of X-rays may be expressed.

7.8. Quality and Tube Voltage. Since the penetration increases with the potential difference across a tube, any device, such as a spark-gap meter or calibrated primary voltmeter, which measures the magnitude of this quantity, provides one means of estimating the penetrating power of the rays leaving the tube. But no matter how exact the device for measuring tube potentials this information in itself, important as it is, is not sufficient to describe accurately the quality of the beam of rays actually utilized. This is true for several reasons. (1) As we shall see presently, there is always a mixture of different kinds of rays leaving a target. (2) Two tubes with exactly the same voltage, do not necessarily emit rays of exactly the same

degrees of penetration. (3) The hardness of what are called characteristic rays (to be discussed later) does not increase steadily with applied voltage. (4) Layers of absorbing material are commonly placed between the tube and the place where the rays are desired, and these *filters*, as they are called, alter the average quality of the rays. More direct means of measuring quality are therefore desirable.

In spite of the fact that a knowledge of the magnitude of the peak voltage across a tube does not give sufficient information to describe quality completely, in actual practice it is always desirable to give the value of this quantity. In this connection L. S. Taylor some years ago gave the following rough classification of the quality of composite beams.

Ultra soft (Grenz) - - - - - -	5 to 10 Kv.
Soft (for diagnosis and superficial therapy) - -	20 to 120 Kv.
Hard (for deep therapy) - - - - -	120 to 250 Kv.
Extra-hard or super-hard, greater than - -	250 Kv.

To this list should be added the ultra-penetrating rays arising from the stopping of electrons possessing many million electron-volts of energy.

7.9. Quality and Half-Value-Layer (H.V.L.). One of the most useful practical means of expressing the quality of a beam of X-rays

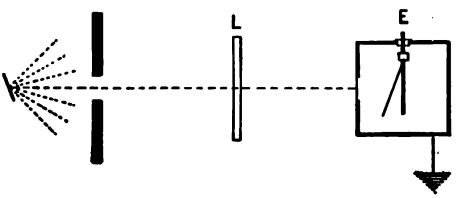


FIG. 7.2. A simple arrangement for examining absorption of a beam of X-rays by an absorbing layer *L*.

consists in giving the *half-value-layer*, that is, the thickness of some standard substance, copper, for example, necessary to reduce the intensity of the beam by 50 per cent. Obviously the more penetrating the beam, the greater the necessary thickness. This method, it will be noticed, deals with the absorption of X-rays by matter, a very important question which, at this stage, we shall discuss only in its simpler aspects. (See Chapter X.)

Suppose an electroscope *E*, Fig. 7.2 (or any other of the devices for measuring ionization to be considered later), is placed in the path of a beam of X-rays, and that ionization readings are taken when successive increasing thicknesses of a material like copper are placed at *L*

in the path of the rays. Results such as those given in Table XI, an actual set taken by Dr. T. G. Stoddard, are obtained. These are plotted in graph 1, Fig. 7·3.

TABLE XI—ABSORPTION OF AN X-RAY BEAM BY COPPER

Thickness of Cu in mm	Intensity
0	100
0·25	63·3
0·5	48·1
0·75	39·3
1·0	30·45
1·25	26·9
1·50	23·0
1·75	20·6
2·00	18·3

From this graph, it can at once be seen that the thickness of copper necessary to reduce the intensity of the beam from 100 to 50 units, that is, a first 50 per cent is about 0·46 mm. If, however, we attempt to describe the quality of this beam by stating that the h.v.l. is

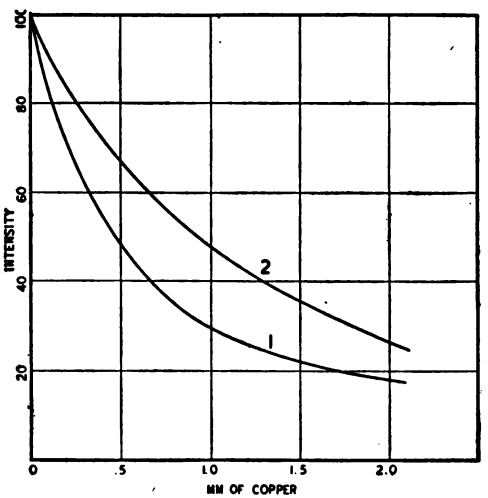


FIG. 7.3. Absorption of a beam of X-rays by increasing thicknesses of copper. In Graph 1 intensity is plotted against thickness, in Graph 2 the logarithm of the intensity.

0·46 mm, we encounter a difficulty. The same graph shows that the additional thickness necessary to reduce the intensity a second 50 per cent, that is, from 50 to 25 units, is not 0·46 mm but more than 0·8 mm. Evidently the penetrating power of the rays which got

through the first 0·46 mm of copper has increased. The conclusion is obvious—*the original beam must have contained a mixture of rays*, some more penetrating than others. The first absorbing layers, therefore, removed a greater percentage of the softer, less penetrating rays, thus transmitting a beam with an excess of harder rays.

It may well be asked: What, then, is the use of describing quality by h.v.l. if, when you work with a beam in the way we have just considered, you do not always get the same result? The answer is that the h.v.l. is not of much value nor generally used unless the beam of X-rays has been filtered *before* any absorption measurements are made, so that the softer components have been almost completely removed. The h.v.l. is then a good general guide to the average penetration of the remainder of the beam, although even then its exact value will depend on the amount of the original filtration. The point is well illustrated by Table XII, which gives some actual observations made by Bouwers and Van der Tuuk on the penetrating rays leaving a tube operated on four different high voltages.

TABLE XII—HALF-VALUE-LAYER

Kilovolts	Filtration 6 mm Cu	Filtration 15 mm Cu
400	5·1 mm Cu	5·7 mm Cu
500	5·4	5·8
550	5·8	6·1
600	6·1	6·4

Note two things. (1) With the same filtration but increasing voltage, the rays are more and more penetrating, as shown by the steady increase in the h.v.l. in either the second or the third column. (2) After increased filtration, in this case 15 mm of copper as against 6 mm, the beam, for any particular voltage, is more penetrating. In the third column, the magnitudes of the h.v.l. are all consistently somewhat higher than those in the second, for the same voltage.

Because of the wide range in the penetrating powers of different kinds of X-rays, the same substance is not suitable for expressing h.v.l. over the whole range. Soft rays, for example, are so readily absorbed by copper that extremely thin sheets would be necessary in making the observations required to determine a h.v.l. Aluminium is therefore often used as the standard substance for soft rays (20 to 120 kV) and for the ultra-soft region (5 to 20 kV) celluloid may be

used. For hard rays (120 to 250 kV) copper is the usual substance, while for the super-hard region, tin has been suggested for 250 to 600 kV, and lead above 600kV.

When it is desired to have an intense beam of rays from a tube operated on low voltage, as in the Machlett tube described in section 5.17, or in some types of tubes used for diffraction studies, it is desirable to reduce the absorption by the walls of the tube itself. For that reason windows made of some low-absorbing material, such as beryllium or lithium, are sometimes used. The marked transparency of beryllium, for example, is shown by calculations made by T. H. Rogers on the total intensity of the radiation from a 50,000 volt Machlett tube transmitted by equal thicknesses of beryllium, aluminium and Pyrex glass. His results show that, if the intensity of the beam transmitted by 1 mm of beryllium is taken as 100, the intensity after passage through 1 mm of Pyrex glass is only 8, and only 5 after passage through 1 mm of aluminium. Lindemann glass, made of oxides of boron, beryllium and lithium, is sometimes used as a material for a window of low absorption. According to data given by Vennart it is not as transparent as beryllium, 0·14 mm of this glass being equivalent to 1·22 mm of beryllium. The element lithium is also remarkably transparent to low voltage X-rays, a plate 1 mm thick absorbing a negligible amount. When lithium is used as the window of an X-ray tube, the outer side must be protected from the action of moisture in the air by a coat of grease or some other suitable material.

Tubes for the emission of feebly penetrating rays have also been built with very thin mica windows.

7.10. Homogeneous Beam and Exponential Law. In Chapter VIII we shall learn that it is possible to separate a beam of X-rays into monochromatic components just as a beam of ordinary light is broken up into its constituent wave lengths. When a *monochromatic* beam of X-rays is examined for absorption in the above manner, it is found that *no matter what the amount of the original filtration*, equal thicknesses of the absorbing material reduce the intensity of the beam by the same fraction; or, in other words, that the h.v.l. remains constant whether the intensity is reduced from 100 to 50 units, or from 50 to 25, or from 25 to 12·5.

Whenever the magnitude of any quantity changes according to such a law; that is, whenever, in the case of X-rays, for each successive equal thickness of absorbing material the intensity decreases by the same fraction, the change follows the *exponential* law. Or, to take an example from radioactivity, whenever for each successive interval of

time, the intensity of the rays from radium decreases by the same fraction, the change is exponential. As this law is of great importance in radiology, the student should try to understand it clearly.

TABLE XIII—AN EXAMPLE ILLUSTRATING ABSORPTION OF A BEAM ACCORDING TO THE EXPONENTIAL LAW

Thickness of Absorber	Intensity	Logarithm of Intensity	Difference in Successive Logarithms
0	100	2·000	
0·25 mm	81·7	1·912	0·088
0·50	66·8	1·825	0·087
0·75	54·7	1·738	0·087
1·00	44·7	1·650	0·088
1·25	36·5	1·562	0·088
1·50	29·9	1·475	0·087
1·75	24·5	1·389	0·086
2·00	20·0	1·300	0·089

In Fig. 7.4 the curved line, which is a plot of the results given in the first two columns of Table XIII, follows the exponential law, that is, it is applicable to the absorption of a pure homogeneous beam of X-rays by successive thicknesses of an absorbing material such as copper. Study it carefully and note the following three things.

(1) To reduce the intensity from 100 to 50 units, or from 50 to 25 requires the same thickness of copper, namely, about 0·86 mm.

(2) If we consider the increase in absorption brought about by the addition of the same thickness, for example, by 0·25 mm of copper, the reduction in intensity is always the same *fractional* amount, whether 0·5 mm is increased to 0·75, or 0·75 to 1·00, or 1·00 to 1·25, etc. Thus, reading off the graph, we find that the first 0·25 mm reduces the intensity from 100 to 81·7 units or about 18 per cent; the second 0·25 mm, from 81·7 to 66·8, or again about 18 per cent; or the third 0·25 mm. from 66·8 to 54·7, once more about 18 per cent.

(3) If the logarithm of the intensity is plotted instead of the actual intensity, the straight line shown in graph 2 of Fig. 7.4 is obtained. This indicates that when absorption follows the exponential law, the log of the intensity decreases by equal amounts (not equal fractions) for equal changes in the thickness of the absorber. The same result is shown by the numbers in the fourth column of Table XIII. If, then, we wish to test whether a curve is exponential or not, a simple

way is to plot the log of the varying quantity, not the quantity itself. If a straight line is obtained, the law is exponential. By way of contrast note graph 2 of Fig. 7.3. Although this is a plot of the log of the intensity of the beam against the thickness of absorber, graph 2

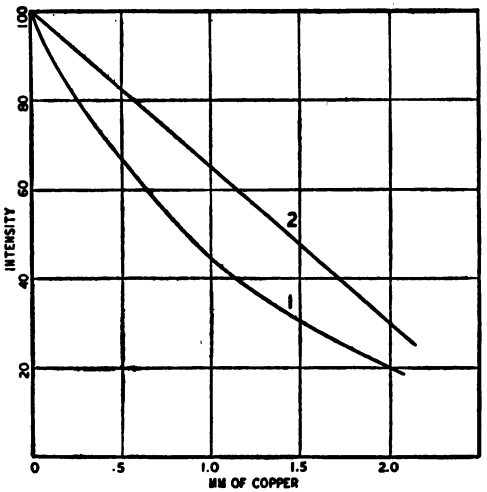


FIG. 7.4. Graphs showing the absorption of a homogeneous beam of X-rays. In Graph 1 intensity is plotted against thickness, in Graph 2 the logarithm of the intensity.

is not a straight line because the absorption of the beam, which is not homogeneous, did not follow the exponential law. More detailed work relating to absorption and the exponential law is given in section 10.10.

7.11. Image Intensifier. In order to explain an important recent advance in fluoroscopy it is necessary to examine further this means of diagnosis. There are several objections to the fluoroscopic arrangement in common use. To avoid the absorption of harmful amounts of radiation by both patient and radiologist,* the intensity of the X-ray beam must be kept low. This has two disadvantages. The viewing room must be darkened and the eyes of the observer " dark adapted ", a procedure which requires time. An even more serious disadvantage is the fact that at the low level of illumination of the fluorescent screen, contrast sensitivity† is very much less than

* Skin doses of 10 to 20 roentgens are not uncommon. (See Chapter XI.)

† Contrast sensitivity is measured by the reciprocal of $\frac{\Delta B}{B}$, where $B \pm \Delta B$ is the brightness of a spot on the screen which can just be distinguished from the surroundings of brightness B.

under normal illumination values. For example, according to Chamberlain, a U.S. authority on fluoroscopy, when a radiograph (a photographed image) is placed on a standard illuminator for viewing X-ray films, a normal eye can detect differences of 1 to 2 per cent between a spot on the film and the surroundings. But, at the level of illumination of a fluorescent screen, even when the eye is dark adapted, differences of 30 to 40 per cent are necessary before contrast can be detected. It is of interest to note that an average value for the brightness (or *luminance* as it is more correctly called) of a fluorescent screen is about 0·001 millilambert, whereas, when a radiograph is being examined on an illuminator, the brightness level is of the order of 30 millilamberts.

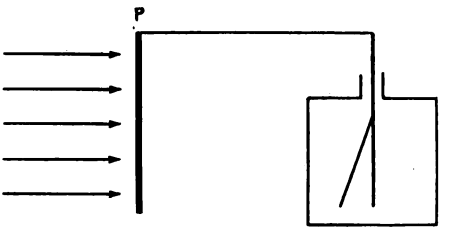


FIG. 7.5. When light of suitable wave length falls on a zinc plate *P* joined to the insulated part of an electroscope, the electroscope if negatively charged loses its charge.

Visual acuity, that is, the ability to see detail is also markedly less at the low levels of illumination. At 30 millilamberts, for example, structures as close as 0·1 mm can be separated by the eye, but, at 0·001 millilambert, neighbouring structures must be nearly 1 mm apart to be seen as two.

The *image intensifier* is a device by means of which an illumination on a fluorescent screen several hundred times greater than in the standard arrangement is obtained with no increase in the intensity of the original X-ray beam.

In this instrument use is made, not only of the fluorescent effect of X-rays, but also of the following important basic ideas. (1) When electrons fall on certain materials, as we have seen in the oscilloscope, they too can cause the emission of visible light. (2) When both ordinary light and X-rays fall on many elements, a *photoelectric emission of electrons* may result. The phenomenon of photoelectricity, which is extremely important in connection with the absorption of X-rays by matter, is discussed in Chapter X. At this stage we are concerned primarily with the photoelectric emission due to

ordinary light, a question so important that it is desirable to examine it carefully before proceeding further with the intensifier.

7.12. Photoelectricity. Suppose an insulated zinc plate *P*, Fig. 7.5, is joined to the knob of an electroscope, and that the system is negatively charged. With proper insulation the leaf of the electroscope remains with deflection unchanged. If, however, light from

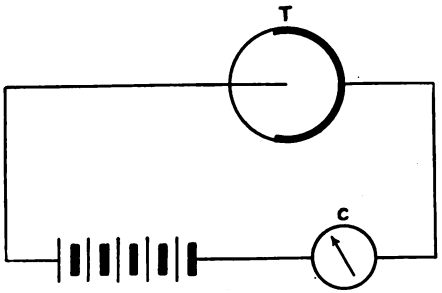


FIG. 7.6. Simple arrangement of photoelectric cell *T* with galvanometer and battery.

an arc lamp is allowed to fall on the metal plate, the electroscope leaf quickly falls. If the system is positively charged, no such discharge takes place. The discharge when the plate is negatively charged is caused by a photoelectric emission of electrons from the surface on which the light is incident. A photoelectric cell is a refined device making use of this principle. In one form, a highly evacuated tube *T*, Fig. 7.6, has an anode consisting of a single wire or ring projecting into the tube, and a cathode, a large area of a metal surface spread over a part of the inside wall. When such a tube is inserted in a circuit, as shown in Fig. 7.6, and light falls on the metallic surface, a current is indicated by the galvanometer *G* because of the photoelectric emission of electrons from the surface.

Other types of cells called *photovoltaic* or *barrier layer* are used, for example in exposure meters in ordinary photography. In these no battery is required because, when light is incident on them, an e.m.f. is developed in the cell itself. The resulting current in a simple circuit including a meter (a galvanometer) is proportional to the intensity of the incident light. In the " photronic cell ", one of this type sold by the U.S. Western Electrical Instrument Company, a thin layer of cuprous oxide is deposited on a copper plate, one terminal of the galvanometer being joined to this plate, the other to a thin metallic film in contact with the outer edges of the oxide.

For any given metallic surface wave lengths longer than a certain critical value do not cause a photoelectric emission. For example, if the experiment described above (Fig. 7.5) is repeated with a piece of red glass in front of the zinc plate, the electroscope is not discharged because the wave lengths transmitted by red glass are too long to cause a photoelectric emission from zinc. If, however, the zinc plate is replaced by a layer of calcium, there is an emission because this element is photosensitive to red light.

The value of the critical or threshold wave length depends markedly on the nature of the surface. Thus, for the element caesium it is 6,810 angstroms, for sodium 5,830, for aluminium 4,770, for silver

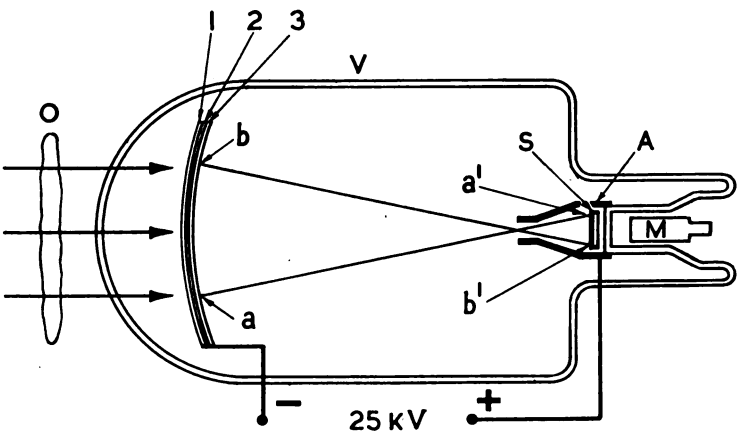


FIG. 7.7. Essential features of an image intensifier. X-rays, after traversing an object *O*, enter the intensifier chamber, falling on a fluorescent screen 2 and a photocathode 3. The electrons emitted by 3 after acceleration by 25 kV, form an electronic image on the screen *S*. Because of the visible light emitted on impact of the electrons at *S*, an image reduced in size, but some 1000 times brighter than the original at 2 is observed. (Adapted by kind permission of Philips Electrical Ltd. from one of their illustrations.)

3,250, for cadmium 3,140, and finally for an alloy of cadmium and magnesium 3,350.

7.13. We return now to the intensifier. Its essential features are explained with reference to Fig. 7.7, an adaptation of a figure used by Philips Electrical in literature relating to an instrument of their design. X-rays after traversing *O*, the object under examination, enter one end of a highly evacuated vessel *V* and impinge on the spherical shaped unit marked 1, 2, 3 forming an image on 2. This unit consists of three layers in close contact, (1) a thin support of aluminium,

(2) a fluorescent screen which emits blue light under the action of X-rays ; and (3), the *photocathode*, made of a material for which blue light causes a high emission of electrons. Since the number of electrons emitted per second is directly proportional to the intensity of the incident blue light, gradations in brightness of the image on screen 2 now appear as corresponding differences in electron emission.

By applying a potential difference of some 25 kV between the photocathode and an anode A at the far end of the tube, and by arranging suitably the resulting electric field so that it acts as an electronic lens, the emitted electrons are both accelerated and focused to form an electronic image pattern on the viewing fluorescent screen S. This pattern is exactly similar to the original pattern on layer 2 adjacent to the photocathode, but is reduced in size. Electrons from the spot a on the cathode, for example, impinge at a' on the screen ; from b at b' and so on.

Since the impinging electrons cause an emission of visible light, in this case a yellow-green (the colour band to which the eye is most sensitive), a final and much more intense fluorescent image appears on the viewing screen. This can be viewed by the naked eye in a room with ordinary illumination, as in an instrument designed by Marconi, or, as in the Philips Intensifier, through a low power binocular. In each instrument, interchangeable devices permit the use of a camera for photographic records. The intensifier has made possible cineradiography and televising a fluorescent image. To quote from Philips literature : " Cinematograph films of the abdomen of normal-sized adults have now been made with skin dose-rates of only a fraction of a roentgen per second."

To prevent the fluorescent light emitted by the screen S from being sent back to the photocathode, with consequent danger of the tube running away, the surface of S is covered with a very thin layer which is opaque to light but not to 25 kV electrons.

In the Philips instrument the gain in brightness over that of the image on screen 2 is of the order of 1,000. This gain is due to two causes. (1) The greater the energy an impinging electron has when it strikes a suitable surface, the more intense the resulting fluorescent light. Due to this cause there is a gain of 10 to 15. (2) A bigger gain is due to the reduction in size of the final image, the linear dimensions in the Philips instrument being reduced by a factor of 9. The electron beam, therefore, is concentrated over an area reduced by a factor of 9^2 or 81, with a corresponding increase in the intensity of the fluorescent light. Due to both factors the overall gain ranges

from about 800 (10 × 81) to about 1,200 (15 × 81). The actual diameter of the final image is 5 inches.

7.14. Photoelectric Timer. In radiography a problem of fundamental importance is the estimation of the exposure necessary to obtain a radiograph with satisfactory overall density. (See section 9.2.) Since frequently this is a matter of judgment based on the experience of the radiologist or radiographer, any method which automatically both estimates, as it were, and terminates the exposure independently of the operator is of great value. The photoelectric timer provides such a method.

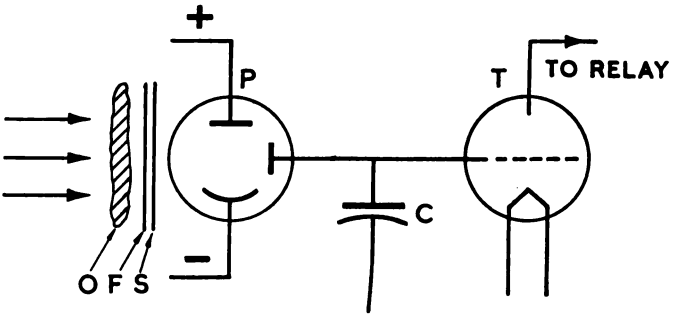


FIG. 7.8. Photoelectric Timer. X-rays after traversing the object *O* fall on a film *F* and a fluorescent surface *S* placed near a photomultiplier tube *P*. As exposure continues, a condenser *C* is charged to a higher and higher potential until such a value is reached that a thyratron *T* fires, thus operating a relay which breaks the X-ray circuit.

Its essential features are shown in the schematic diagram of Fig. 7.8. A beam of X-rays, after traversing *O* the object being radiographed, falls on both the film *F* and a fluorescent surface *S* placed near a photoelectric tube *P* (of the photomultiplier type described in section 12.8). The greater the overall intensity of the beam of X-rays leaving the object, the greater the intensity of the light emitted by *S* and hence the greater the resulting current in a circuit containing the photoelectric tube. Now, as the exposure continues, because of this current, a condenser *C* is charged to a higher and higher potential and at the same time the value of the bias on the grid of a thyratron* *T* continually alters. When the bias reaches a certain value the thyratron " fires ", the resulting current operating a relay which breaks the X-ray circuit and ends the exposure. Pre-

* A thyratron is a tube, often a triode, filled with a gas like argon or with mercury vapour, which suddenly becomes conducting or " fires " when the negative bias on the grid bears a certain relation to the plate voltage. Being gas filled, a thyratron can carry a much larger current than an ordinary triode tube.

liminary adjustments must of course be made to ensure that for a given film the thyratron fires when the correct exposure to give satisfactory density has been made. But once such an adjustment has been made, this type of timer ends an exposure automatically whether an intense beam is used for a short time or a less intense beam for a corresponding longer time. There is no setting of a predetermined time as in the triode timer.

PROBLEMS AND QUESTIONS

1. What effect has the speed of cathode rays on the nature of the X-ray beam originating when the rays are stopped?

2. Describe a simple experiment to show that in general a beam of X-rays consists of a mixture of hard and soft.

3. Explain the purpose of an intensifying screen, as well as the principle underlying its use.

4. Describe six properties of X-rays.

5. Describe two applications of the fluorescence excited by X-rays in radiology.

6. How would you test an X-ray beam (without using a spectrometer method) to see whether it is homogeneous, or not?

7. A homogeneous beam of X-rays has a penetrating power such that the half-absorption value of aluminium is 2 mm. How much will the intensity of such a beam be reduced by 8 mm of aluminium? *Ans.* 93·75 per cent.

8. The intensity of a filtered beam of X-rays is examined before and after passing through layers of aluminium 1, 2, and 3 mm thick and ionization values of 100, 80, 64, and 51·2 are obtained. (*a*) Is this beam homogeneous and if so, why? (*b*) What is the h.v.l.? *Ans.* (*a*) yes ; (*b*) 3·1 mm.

9. Explain what is meant by h.v.l.

10. What is the general effect of a filter on a beam of X-rays?

11. Explain how the h.v.l. of a beam of X-rays is altered when the tube voltage is increased.

12. How is the quality of a beam of X-rays as measured by the h.v.l. method related to : (i) the p.d. across the X-ray tube ; (ii) the filtration used?

CHAPTER VIII

MEASUREMENT OF WAVE LENGTH OF X-RAYS

8.1. Reflection of X-rays. It is important to realize that the work of von Laue and his colleagues in 1912 proved without any doubt that X-rays had a wave nature just like ordinary light. Before that date other experimenters had tried with some success to prove the wave nature of X-rays. One of the simplest of the early experiments consisted in examining whether or not there was any spreading out when the rays fell on a narrow aperture. Although the results of experiments of this kind were not conclusive they did provide evidence that, if X-rays had a wave nature, the wave lengths must be of the order of 10^{-8} or 10^{-9} cm. With this evidence in mind, it occurred to von Laue that a crystal, whose regular structure was known to have a spacing between atom layers of the order of 10^{-8} cm might act towards X-rays much the same as a diffraction grating acts towards light. The idea was tested by experiment and proved to be one of the most fertile in modern science.

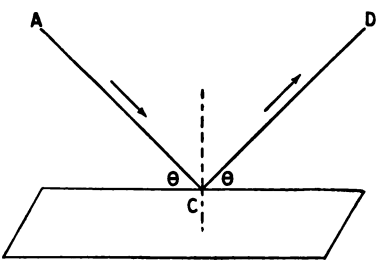


FIG. 8.1. An X-ray beam along AC under certain conditions is regularly reflected from the face of a crystal along CD.

In Laue's original experiment a narrow beam of X-rays traversed a zinc blende crystal, and the emergent beam fell on a photographic plate. On development the plate showed a regular pattern of bright spots on a dark background. In interpreting this result W. L. Bragg of England showed that it was possible to look on cleavage planes of crystals as reflecting surfaces and, subsequently, in collaboration with his father, Sir William Bragg, developed a technique which proved of tremendous value for the analysis of an X-ray beam as well as for the examination of structure of crystals.

Consider a narrow beam of X-rays, represented by AC in Fig. 8.1, incident on the face of a crystal in a direction making an angle θ with this face. The question arises: Is there a reflected beam in the

direction CD, as there is if AC represents a beam of light and the crystal face is replaced by a mirror? According to Bragg's ideas, which experiment soon verified many times over, a cleavage plane of a crystal with its very regular arrangement of atoms, acts as a mirror for X-rays, nature providing the smooth surface necessary to reflect regularly waves as short as those of X-rays. The reflection of X-rays from a crystal, however, differs in one important respect from optical reflection at a mirror. Since X-rays penetrate matter, there is a series of reflections from successive parallel planes of atoms. The beam CD, therefore, in reality consists of a number of superimposed beams, each reflected from a different plane of the crystal.

Now let us enlarge the scale of our diagram sufficiently to show successive layers, as we have done in Fig. 8.2, for four layers. Then,

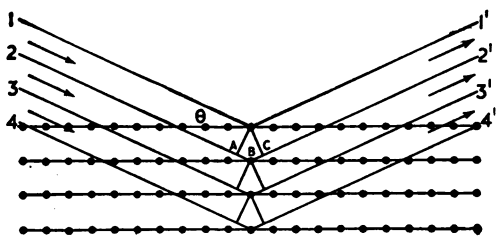


FIG. 8.2. Reflection of X-rays from successive parallel planes of atoms in a crystal.

remembering that the planes are separated distances not much greater than 10^{-8} cm, we see that even a narrow beam like AC when enlarged on the same scale, will, in Fig. 8.2, be represented by several lines such as 1, 2, 3, 4, with corresponding reflected rays 1′, 2′, 3′, 4′. Moreover, it is not difficult to see that the path of the disturbance along 11′ is shorter than that along 22′, 22′ shorter than 33′, and so on. For disturbances 11′ and 22′ this path difference is equal to $AB+BC$ as shown in Fig. 8.2. With a little simple trigonometry, this can readily be shown to be equal to $2d \sin \theta$, where d is the distance between successive layers, and θ is the angle which the beam of rays makes with the face of the crystal. For any successive pairs of disturbances, the path difference will be the same.

We see then, that the beam CD of Fig. 8.1, really consists of a superposition of a number of beams, with a path difference between every successive pair equal to $2d \sin \theta$. It follows that all the component beams will unite to form a resultant intense beam only if this path difference is equal to one, or two, or three or more wave lengths,

because the beams will then all be in phase. *This means that when a beam of homogeneous X-rays is incident on the face of a crystal, there is a reflected beam of marked intensity only for very special angles of incidence. If the incident beam contains a number of different wave lengths, then, for any given angle of incidence, there is an intense reflected beam only if there is a component whose wave length* λ *is such that* $\lambda = 2d \sin \theta$, or $2\lambda = 2d \sin \theta$, *etc.* Analysis of a beam is possible, therefore, because each component is reflected in a direction different from any of the others. By rotation of a crystal to vary the angle of incidence, it is then possible to spread out a beam of X-rays into first, second, third order spectra, just as in the case of the diffraction grating in light. Frequently we are concerned only with the first order, and in this book we shall confine our attention to that order.

8.2. X-ray Spectrometer. A common arrangement for applying the above principle to the analysis of a beam of X-rays is shown in Fig. 8.3. A narrow beam of X-rays, after passing through the slits S_1 and S_2 cut in thick blocks of lead, is incident on the face of a crystal C set on the table of the spectrometer. By means of a scale

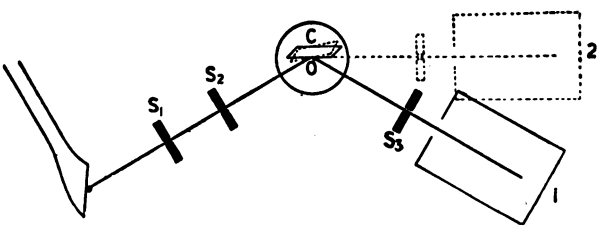


FIG. 8.3. Diagram showing the essentials of an X-ray spectrometer with ionization chamber.

rotations of the crystal through small angles may be measured accurately. A third slit S_3 is so placed that any reflected beam which exists may enter an ionization chamber I placed immediately behind it. This slit must of course be placed so that the line OS_3 makes the same angle with the face of the crystal as the incident beam. Since for each position of the crystal there is only a single correct position of the slit S_3 and the ionization chamber, these are mounted on an arm by means of which they may be rotated about the central axis through O.

In actual use, the incident beam of rays to be analysed is allowed to strike the face of the crystal at a number of different angles. For each angle, slit S_3 and the ionization chamber are set in the correct position

and the ionization current, if any, measured. A graph is then made showing the way in which the ionization current varies with the angle of incidence. Alongside the axis on which the angles of incidence are plotted a wave length scale may be marked by using the fundamental relation $\lambda = 2d \sin \theta$, provided that a crystal with known d is used. Examples of such graphs are given in Fig. 8.5 and Fig. 8.6. These will be discussed presently.

8.3. X-ray Spectrograph. The ionization chamber may be replaced by a photographic plate and a permanent record obtained of the X-ray spectrum. By way of illustration, reference is made to the *Seeman Spectrograph*, an instrument, especially designed for radiolo-

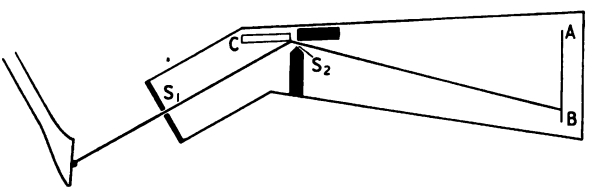


FIG. 8.4. The Seeman X-ray spectrograph.

gists, which is small and compact and does not require as much experimental skill as the above spectrometer. The beam to be analysed enters the instrument through a narrow slit S_1, Fig. 8.4, is incident on the face of a crystal immediately behind which a second narrow slit S_2 allows any reflected beam which may be present to emerge and strike a photographic plate in position AB. By means of a clock-work mechanism the portion of the instrument holding the crystal and the plate is kept in a regular oscillatory motion about the second slit as axis. In this way the original beam strikes the crystal behind S_2 at a series of different angles and regular reflection of each component takes place in the way we have already described. Wave lengths may be calculated by the use of $2d \sin \theta$, but actually the manufacturer of this instrument provides a scale by means of which wave lengths may be read off directly from the photographic plate.

8.4. Shortest Wave Length. The graph of Figs. 8.5 and 8.6, made from observations by the late Dr. Duane, a prominent X-ray worker at Harvard University, are typical of results obtained with the ionization chamber. The graphs show clearly two things: (1) there is always a range of wave lengths in the beam leaving the target of a tube; and (2) there is a very critical minimum wave length at which radiation begins. Experiment shows that this shortest wave

length depends solely on the *maximum* voltage across the tube, and that these two quantities are connected by the following simple relation:

$$\text{shortest wave length (in angstroms)} = \frac{12345^*}{\text{maximum voltage}}.$$

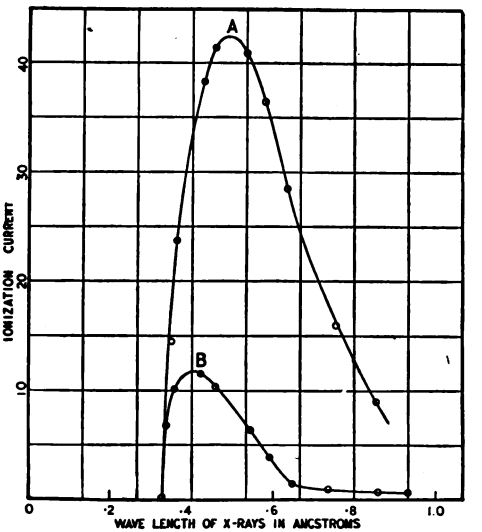


FIG. 8.5. Graphs showing the analysis of a general beam of X-rays by a spectrometer: *A*, without filter, *B*, with filter.

For example, with 80,000 volts as peak value, the shortest wave length is about 0·15 angstrom. With 250,000 volts, the shortest is 0·049 angstrom. Although the shortest wave length is not the most intense (note again the graphs of Fig. 8.5), a knowledge of its value give some indication of the quality of the beam.

If the shortest wave length can be read off a scale provided with such an instrument as the Seeman Spectrograph, the above relation provides us with an accurate method of measuring tube voltage. (See again, section 2.11.)

8.5. General and Characteristic Radiations. An examination of Fig. 8.4 and Fig. 8.5 will show that the graphs differ in one important respect. In each of those in Fig. 8.5, the radiation covers a continuous range, beginning at the critical minimum wave length, then rapidly increasing to a region of maximum intensity, beyond

* Although the number 12345 is a little in error, being more accurately written $12{\cdot}4 \times 10^3$, the error in using the easily remembered 12345 is less than one per cent, an accuracy usually quite sufficient in radiology.

which the intensity gradually decreases until the radiation ceases. In each of the graphs of Fig. 8.6, there is an additional feature, because isolated peaks of marked intensity occur at certain critical wave lengths.

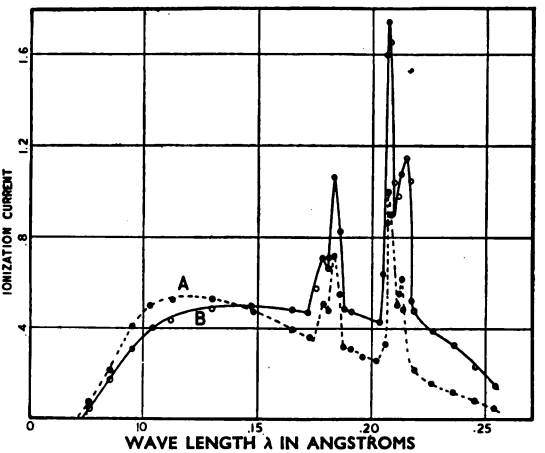


FIG. 8.6. Graphs showing the presence of characteristic X-rays: *A*, with filter 1 mm of copper; *B*, with filter 12 mm of aluminium.

The same two types of X-ray radiation are shown photographically in Fig. 8.7, in which each spectrogram corresponds to a different tube voltage. These photographs show clearly: (*a*) the continuous radiation, beginning at a critical wave length, whose magnitude varies with the applied voltage; and (*b*) the superposition, in all but number 10, of isolated wave lengths. The values of these isolated wave lengths, which as we shall see are not always present, depend on the nature of the target. The continuous range is called the *general* or *white* or *independent* radiation; the isolated wave lengths, the *characteristic* radiation. The continuous range is an example of *bremsstrahlung* (German *bremsen*, to brake) a name given to X-rays which originate in the irregular slowing down of electrons after hitting a target.

8.6. White Radiation. The total intensity of the beam of continuous rays depends on the following factors:

(*a*) *The Current through the Tube.* Double the current, and the intensity is doubled; or, more generally, the intensity is directly proportional to the current.

(*b*) *The Tube Voltage.* The intensity increases as the voltage across the tube increases, the variation being approximately as the square of the voltage. The factor is made use of in the grid action tube

(see Fig. 5.8) when this tube is used with pulsating voltage. Because of the repulsive action of the extended front of the cathode on the electrons, less current is passed at low voltage and more at high

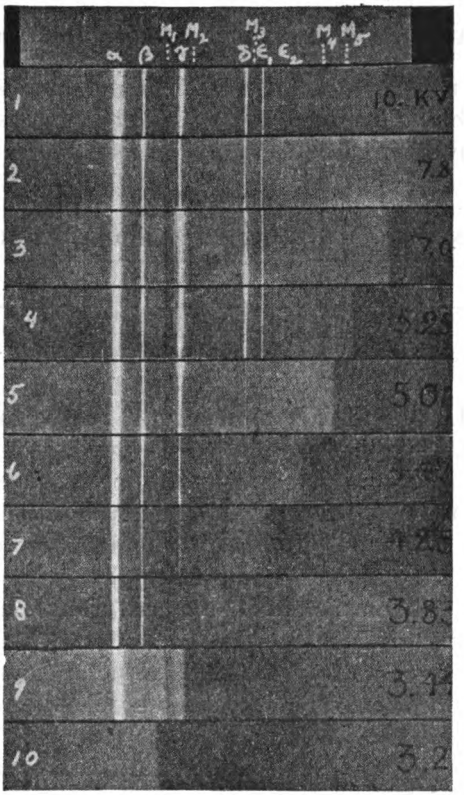


FIG. 8.7. Spectrograms showing short wave length limits at different voltages, as well as characteristic rays. In this figure, wave lengths increase from right to left. (Ross.)

(because of the V^2 law), with consequent gain in output of X-rays. This increased output shortens exposures when diagnostic grid tubes are used.

(*c*) *The Atomic Number of the Metal Used as a Target.* The higher the atomic number, the more intense is the beam.

8.7. Characteristic Rays. Characteristic rays do not appear at all unless the tube voltage is sufficiently high. That is the reason none appear in the graphs of Fig. 8.5, nor in spectrum 10 of Fig. 8.7. With tungsten as target, potentials in the range 80,000 to 100,000 are necessary, and with uranium, characteristic rays are not emitted

until nearly 115,000 volts are applied to the tube. The necessary voltage is proportional to the square of the atomic number. Thus, platinum, of atomic number 78, requires a voltage which is higher than that for tungsten, atomic number 74, by the factor $\frac{78 \times 78}{74 \times 74}$.

It is well to note that, the higher the atomic number, the shorter the wave length of corresponding* rays. This point is illustrated by the numbers given in Table XIV.

TABLE XIV

CORRESPONDING WAVE LENGTHS OF FOUR ELEMENTS

	Copper	Silver	Tungsten	Uranium
Wave Length -	1·54	·56	·21	·15
Atomic Number -	29	47	74	92

8.8. Wave Length and Penetration. Wave length measurements show that in radiology the range extends from about 1·0 to possibly 0·05 angstrom. By means of the spectrometer a beam may be separated into its constituent wave lengths and the absorption of each examined separately. The results of such investigations show that in general† the shorter the wave length, the more penetrating the beam. For example, using the numbers given in first and fourth columns of Table XV, we note that for $\lambda = 0{\cdot}064$, the h.v.l. in aluminium is 19·7 mm; for $\lambda = 0{\cdot}13$, 13·7 mm; and for $\lambda = 0{\cdot}26$, 6·35 mm. For the same three wave lengths, the h.v.l. in copper are 3·9 mm, 1·36 mm, and 0·24 mm.

The numbers in Table XIV show that if feebly penetrating (very soft) characteristic rays are wanted, targets made of metals of low atomic number should be used.

8.9. K, L, and M Rays. An analysis of all the characteristic wave lengths emitted by a single element shows that they may be divided into groups. Table XVI, for example, gives the wave lengths in angstroms of three groups emitted by the element tungsten.

In accordance with certain theoretical ideas to be explained presently, the three groups are designated *K*, *L*, and *M*. A glance at the table will show that the wave lengths in the *L* and *M* groups are so long that ordinarily they are not used in radiology. Some of them are so soft that they are completely absorbed by the glass walls of a tube.

* In section 8.11, the meaning of corresponding wave lengths is explained.

† See, however, section 10.8.

TABLE XV—HALF-VALUE LAYERS FOR A FEW WAVE LENGTHS

Aluminium

λ	μ/ρ*	μ*	h.v.l.
0·064	·130	·351	19·7 mm.
·098	·156	·421	16·4
·13	·186	·502	13·7
·175	·228	·616	11·2
·2	·270	·729	9·5
·26	·402	1·685	6·35

Copper

λ	μ/ρ*	μ*	h.v.l.
·064	·198	1·76	3·9 mm
·098	·325	2·89	2·38
·13	·57	5·07	1·36
·175	1·12	9·97	·69
·2	1·59	14·15	·49
·26	3·25	28·9	·24

TABLE XVI—CHARACTERISTIC RAYS OF TUNGSTEN†

K	*L*	*M*
·213	1·48	8·98
·208	1·47	8·94
·185	1·28	8·56
·184	1·24	7·34
·179	1·09	6·97
—	—	6·95
—	—	6·93
—	—	6·79
—	—	6·74
—	—	6·12
—	—	6·07
—	—	5·62
—	—	5·34
—	—	5·16

* The meaning of these symbols is explained in sections 10.10 and 10.14.
† Values taken from *X-rays in Theory and Experiment* by Compton and Allison, D. Van Nostrand Company.

Individual lines in any group such as the K are often designated by Greek letters. For example, the most intense wave length in the K group of tungsten, 0·208 angstrom, is called the $K\alpha_1$ line; 0·213 is the $K\alpha_2$ line; 0·184, the $K\beta_1$, 0·179 the $K\beta_2$; and so on.

8.10. Interpretation of K, L, and M Wave Lengths. In order to give an explanation of the origin of characteristic rays, we must amplify the picture of the atom given in section 3.6. It was there pointed out that an atom of atomic number Z consists of a nucleus with a positive charge of Z electronic units surrounded by Z electrons. A large number of experimental facts have led physicists to the view that the electrons are arranged around the nucleus in groups or in what are sometimes called shells, designated by the letters K, L, M, N, O, ... In a helium atom ($Z=2$), for example, there is only a K group of 2 electrons; in lithium ($Z=3$) a third electron appears in the L group; in copper ($Z=29$) there are 2 electrons in the K group, 8 in the L group (arranged in 3 sub-groups); and 18 in the M group (in 5 sub-groups); also one in the N group. If the student will recall the explanation of ionization given in section 3.7 and remember that the larger Z, the greater the positive charge on the nucleus, he will realize that, at any given distance from the nucleus, an electron is attracted to the nucleus more strongly in an atom of high atomic number than in one of low. If he remembers further that the electric attraction between charges of opposite sign falls off inversely as the square of the distance, he will have no difficulty in seeing that outer electrons are attracted much less than those nearer the nucleus. It follows that in an atom of low Z the work necessary to remove an outer electron away from the atom is much less than the work required to remove an inner electron from an atom with a high value of Z. To give concrete examples, it requires less than 5·3 electron-volts to ionize a lithium atom, but more than 69,000 eV to remove a K electron from a tungsten atom. To remove an electron from the L group in a tungsten atom requires about 11,300 eV.

A normal atom is a stable system which cannot radiate energy until it has been ionized or put into what is called an *excited state*. This can be done by adding energy to the atom either by electronic bombardment or as we shall see later, by the absorption of radiation. In order to account for the isolated wave lengths which appear in both optical and X-ray spectra, pioneers like the Danish physicist Bohr had to introduce certain somewhat revolutionary ideas. According to these, when excess energy is given an atom, it is put into one of a number of *stationary states* or *energy levels*, characterized by what

are called *quantum numbers*. If subsequently the atom reverts from a higher to a lower state or level, or to the lowest state or *ground level*, energy is emitted in the form of radiation in an amount equal to the difference in energy between the higher and the lower levels. Moreover, for each transition from one state to another, a *quantum* or a packet of radiant energy is emitted. The magnitude of a quantum is $h\nu$, where h is a number called *Planck's constant* in honour of the physicist who first introduced the conception of quanta, and ν is the frequency of the emitted radiation. Since $\text{frequency} = \frac{\text{velocity}}{\text{wave length}}$ or $\nu = \frac{c}{\lambda}$, where c is the velocity of all electromagnetic waves, we may write

$$h\nu = \frac{hc}{\lambda} = \text{energy change resulting from the electron jump, or}$$

$$\frac{1}{\lambda} = \frac{\text{energy change}}{hc}.$$

It follows that *the greater the energy change, the shorter the wave length emitted.* In optical spectra we are concerned with outer electrons and small charges in energy, and hence with wave lengths much longer than those encountered in X-rays, where the energy changes are many times greater.

We can now look in a little more detail at the origin of characteristic X-rays.

In order to put an atom in the state where the emission of all of its characteristic X-rays is possible, first of all the atom must be ionized by the removal of an electron from the K shell. This may be done by electronic bombardment of a target, or, as we shall see in the next chapter, by absorption of a beam of X-rays of suitable wave length. When an electron has been so removed, its place subsequently is filled by another electron coming in or " dropping " in from one of the surrounding shells. If the drop is from the L shell, there is a certain energy gain and a characteristic ray of a definite wave length is emitted. If the drop is from the M shell to the K shell, the energy gain is greater, and a shorter wave length is emitted. For a drop from the N shell to the K shell, the emitted wave length is still shorter. The K group of wave lengths, then, corresponds to electron drops or transitions from various outer shells or energy levels into the K level. In Fig. 8.8, 1, 2 and 3 represent three wave lengths in this group.

If an electron has dropped from the L to the K level, the vacancy thus created in the L shell must be filled, and hence we have an L group of wave lengths corresponding to transitions from outer levels to the L level. In Fig. 8.8, 4 and 5 represent two such wave lengths. Because of the smaller change in energy involved in transitions which end on the L level instead of the K, the corresponding wave lengths are longer. (See again Table XVI.)

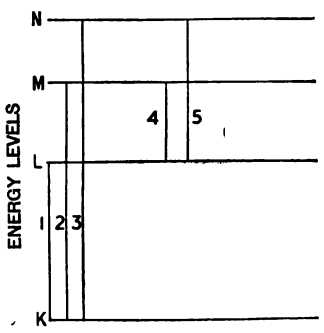


FIG. 8.8. Schematic diagram to depict the emission of K X-ray wave lengths by electron transitions to the K shell; and of L wave lengths by transitions to the L shell.

In the same manner we may have an N group of still longer wave lengths corresponding to transitions of an electron from outer shells or levels to the N level.

In Table XVI, it will be noted, especially for the M group, that more wave lengths are listed than might be expected from the above explanation. This is due to the fact that the electrons in any one shell or level, such as the M, are arranged in subshells, and that, in consequence, the energy change when an electron goes from one subshell of the M level to the K level, is slightly different from the change corresponding to a transition from another subshell of the M level to the K level.

It will be seen later in connection with the disintegration of radioactive atoms that *nuclei* of atoms may exist in excited states or levels (see section 15.11 and Fig. 15.5). When there is a transition from one excited state of the nucleus to a lower one, highly penetrating X- or gamma rays are emitted.

8.11. Meaning of Corresponding Wave Lengths. In section 8.7 reference was made to the fact that the greater the atomic number of an element, the shorter the wave length of a corresponding ray. (See again Table XIV.) By corresponding rays we mean those which arise from the same transition in energy levels. Thus, for all elements, the wave lengths emitted when an electron drops from the L level to the K, or more exactly from the same sublevel of the L shell to the K, are corresponding. The reason why the wave lengths of such rays get shorter as the atomic number Z gets larger, has already been pointed out. The greater Z, the greater the positive charge on the nucleus, hence the greater the attraction of the nucleus

for a K electron, hence the greater the work which must be done to remove a K electron out of its shell. When an electron returns to the K shell, there is, therefore, a greater gain in energy, and a shorter wave length is emitted.

8.12. Effective Wave Length. In the above sections we have explained how a beam of X-rays may be analysed into its constituent wave lengths. Although such an analysis is the ideal way of describing the quality of a beam, the practical radiologist can scarcely be expected to examine quality in this way. He can, however, make use of wave length measurements obtained by other workers under laboratory conditions and by means of them record what is called the *effective wave length* of the beam he is utilizing. The meaning of effective wave length may be defined in several ways.

(1) In terms of h.v.l.

Suppose an operator is provided with a table giving the h.v.l. in copper for a series of monochromatic wave lengths, such as we have given in Table XV. If, then, without any analysis into constituent wave lengths, he determines the h.v.l. for the beam he is using, he can read off from his table the wave length of the monochromatic beam which has this same h.v.l. That wave length would then be taken as the effective wave length of his beam.

(2) Through the absorption of a particular thickness of a standard substance.

It is a simple matter to determine the percentage reduction in intensity of an unanalysed beam brought about by, say, $\frac{1}{2}$ mm of copper. This requires only two readings with an instrument like an electroscope, one of the rate of fall before the introduction of the layer of copper, the other, after the copper is in place. If, now, the operator is provided with a graph or a table giving the percentage absorption of $\frac{1}{2}$ mm of copper for a whole range of monochromatic wave lengths, he again can read off the value of that particular wave length which has the same percentage absorption as that of the beam he is using. This gives him his effective wave length.

Alternately, from the percentage absorption by the copper of the beam under examination, it is not difficult to calculate the absorption coefficient. (See section 10.10.) Then, from a formula connecting the coefficient with the wave length, the value of the monochromatic wave length which has the same coefficient can be calculated. This gives the effective wave length.

When this method is used, care must be exercised to specify the particular thickness of standard absorbing material used, because

somewhat different values of λ are obtained for each thickness. For example, in one investigation Dr. Edith Quimby, of the Memorial Hospital, New York, showed that with a 1/10 mm of copper, 59 per cent of a beam was transmitted, and λ was found to be 0·235 angstrom; with 0·47 mm of copper, 50 per cent was transmitted, and λ was 0·208 angstrom; and with a layer of copper 1 mm thick, the transmission was 35 per cent, and λ 0·182 angstrom.

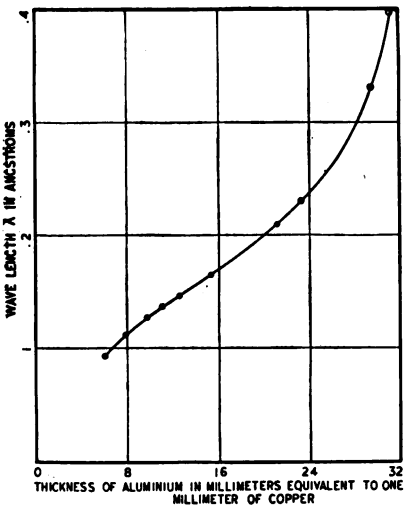


FIG. 8.9. Standard graph (*after Duane*) for determining effective wave length.

The reason for such differences in the value of the effective wave length of a mixed beam of X-rays is due to the fact that, in general, longer wave lengths are absorbed to a greater degree than shorter ones. As already pointed out in section 7.9, a beam containing a mixture of different kinds of rays becomes progressively harder, the greater the thickness of the absorbing material through which it passes. Hence, in methods (2) and (3), the copper used as an absorber actually alters the average penetration of the beam which is being measured by an amount which is greater, the greater the thickness. It follows that the measured effective wave length should become shorter and shorter, the greater the thickness of the absorber. It also follows that the thinner the thickness of the copper used as a standard absorber, the more nearly the measured wave effective length represents that of the original beam.

(3) Through the ratio of equivalent thicknesses of two standard substances.

The graphs of Fig. 8.6 illustrate the important fact that the *relative* absorbing powers of two different substances vary with the wave length. From these graphs, for example, we note that 1 mm of copper is a more effective absorber than 12 mm of aluminium for wave lengths longer than 0·141 angstrom, but less effective for shorter wave lengths. Expressing this fact in another way we say that the particular thickness of aluminium which absorbs a beam of X-rays to the same extent as 1 mm of copper varies with the wave length. Such equivalent thicknesses of aluminium, as determined by Duane, are plotted in Fig. 8.9. By means of such a graph an operator can determine the effective wave length of a beam in still another way. All that is necessary is to determine by actual experiment: (1) how much the beam is reduced in intensity by 1 mm of copper; and (2) by using increasing thicknesses of absorbing layers of aluminium, the particular thickness which reduces the intensity of the beam by the same amount as the millimetre of copper. Suppose the equivalent thickness of aluminium was 16 mm. Then from this graph, we read off that, for a monochromatic wave length equal to 0·17 angstrom, 16 mm of aluminium absorbs to the same extent as 1 mm of copper. By this method, then, 0·17 angstrom is the effective wave length of the mixed beam.

PROBLEMS AND QUESTIONS

1. Describe with diagram the spectrometer method of measuring in angstroms the constituent wave lengths in a beam of X-rays. Indicate on what two quantities the magnitude of the calculated wave length depends.

2. A beam of X-rays, consisting of both general and characteristic rays, is analysed with an ionization chamber and a spectrometer. Indicate the nature of the graph you would obtain. If a photographic method were used, what results would you obtain?

3. Explain why the Seeman spectrograph can be used as a voltmeter.

4. An X-ray tube is operated on 150,000 volts. What is the shortest wave length emitted? *Ans.* 0·082 angstrom.

5. If the analysis of an X-ray beam showed the shortest wave length to be 0·1 angstrom unit, what maximum voltage is applied to the tube?

6. Why can an X-ray spectrometer be used as a high tension voltmeter? An X-ray tube is operated at a constant voltage. Draw a rough graph to illustrate the character of the rays emitted. If the voltage is equal to 200,000, what will the shortest wave length be?

7. What is meant by the effective wave length of an X-ray beam? Explain the fundamental principle involved in its determination by means of a Duane standard graph.

8. Show by a graph the distribution in intensity of X-rays with wave length when a tube is operated at constant potential. Indicate any differences that you might expect if the operating voltage were changed from say 50,000 volts to 200,000 volts.

9. In a *few words*, explain why, as a rule, L and M radiations are of no importance in radiology.

10. An X-ray tube with a tungsten target is operated at p.d. of (i) 40,000 volts ; (ii) 100,000 volts. In each case the beam of X-rays is examined with a spectrometer and ionization chamber. If ionization is plotted against wave length, draw, very approximately, the type of curve obtained for each case, marking clearly the shortest wave length observed, and any outstanding difference between the two curves.

11. Radium C emits gamma rays of wave length 0·06 angstrom. What voltage would be necessary to obtain X-rays of this wave length?

12. What is the general effect of a filter on a beam of X-rays?

13. A betatron develops electrons possessing 100 MeV of energy. If the electrons are made to strike a target, estimate the shortest wave length of the resulting X-rays. *Ans.* 0·000123 angstrom.

14. (*a*) If it requires 25·6 keV to excite all the K wave lengths of silver, and if the mean wave length of the K_α lines is 0·561A, estimate how much work is required to remove an electron from the L shell. *Ans.* 3·5 keV.

(*b*) If an electron possessing 18 keV bombards a silver target, estimate the kinetic energy of the liberated L electron. *Ans.* 14·5 keV.

15. You are given that 69·3 keV are necessary to excite the K wave lengths of tungsten and 10·4 keV to excite the L wave lengths. Estimate the mean wave length of the K_α lines.

CHAPTER IX

RADIOGRAPHY, MICRORADIOGRAPHY AND TOMOGRAPHY

9.1. In section 5.11 a brief reference was made to the necessity of using a small focal spot to obtain radiographs of good definition. In this chapter we begin by a discussion of the important factors which must be considered in obtaining a satisfactory radiograph. Particular reference is made to: (*a*) density; (*b*) contrast; (*c*) lack of sharpness; (*d*) resolution.

9.2. Density. Most students are aware that a photographic emulsion consists of a silver halide, frequently silver bromide, in the form of grains of microscopic size, suspended in gelatine. When the emulsion is exposed to light or to X-rays, such a change takes place in some of the halide grains that on applying a developer, or reducer, to the emulsion the bromine or chlorine is removed from these grains and metallic silver is deposited. After development, a fixing solution or fixer neutralizes the remaining traces of developer left on the film and dissolves the undeveloped halide left on the emulsion. A blackened image, the negative, is then seen on the film carrying the emulsion. In general, the greater the exposure, E, that is, the product (intensity of light or X-rays $\times$ time), the greater the degree of blackness or the *density* of the image. In radiography density is a very important quantity, whose magnitude D, at any given spot on the image is given by the relation

$$D = \log \frac{L_0}{L_i}, \tag{1}$$

where L_0 is the intensity of a beam of light incident on the film at the spot in question and L_i is the emergent intensity. For example, if a radiograph is viewed by placing it on an illuminator and it is found that the incident light on a spot is 10 times more intense than the emergent, D has the value 1. If the ratio of incident to transmitted intensity is 20 to 1, $D = \log 20 = 1{\cdot}3$.

9.3. Contrast. *Contrast* has reference to the difference in density between adjacent parts of a film. Quantitatively, the contrast C at a given part of a film is measured by the difference between the density

at that part of the image and that of the surroundings. It follows at once that

$$C = D_i - D_s, \tag{2}$$

where D_i = density at a spot on the film and

D_s = density of the surroundings.

If the film is viewed on an illuminator and L_0 is the intensity of the incident light, L_i and L_s, the emergent intensities at the spot and the surroundings, it follows also that

$$\begin{aligned} C &= D_i - D_s \\ &= \log \frac{L_0}{L_i} - \log \frac{L_0}{L_s} \\ &= \log \frac{L_s}{L_i}. \end{aligned} \tag{3}$$

9.4. Meaning of Gamma. Contrast depends to a marked degree on what is called the *gamma* (γ) of the developed image.

The value of γ is found from the graph obtained when the density of a film is plotted against the logarithm of the exposure E, to give what is called the *characteristic curve*. Its general nature is shown in Fig. 9.1. It consists of the toe T, a curved part at the beginning, the shoulder S, another curved part at the end, and a main portion which is either a straight line or approximately so. The slope of the straight line, that is, the tangent of the angle CAB is called the gamma of the developed image. If this angle $=45°$, $\gamma = 1$.

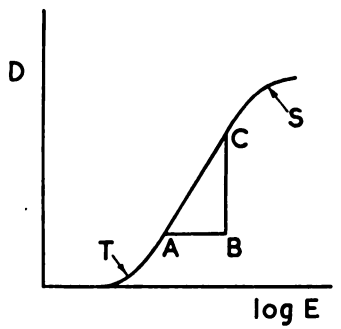


FIG. 9.1. Characteristic curve for a developed image, in which the density D is plotted against the logarithm of E, the exposure.

For a given film, the value of γ depends on the time of development, the slope increasing with increasing time up to a maximum obtained with lengthy development. It should now be clear that the greater the value of γ, the greater the contrast. Using symbols and Fig. 9.1, we may write

$$\gamma = \frac{D_i - D_s}{\log E_i - \log E_s},$$

from which

$$\begin{aligned} C &= \gamma(\log E_i - \log E_s) \\ &= \gamma \log \frac{E_i}{E_s}. \end{aligned} \tag{4}$$

Since at all parts of a radiograph the times of exposure are the same, relation (4) may be written

$$C=\gamma \log \frac{I_i}{I_s}, \tag{5}$$

where I_i is the intensity of the *X-ray beam* incident at a spot on the image and I_s is the intensity incident on the surrounding area.

9.5. Unsharpness. In a perfect image an object with clear-cut edges would be reproduced with edges equally clear-cut. In actual practice, there is a certain amount of blurring or lack of sharpness at the edges. This is usually called *unsharpness.* Quantitatively, unsharpness is measured by the rate at which the density changes as one passes through the edge of an image to the surroundings. It is commonly described by giving the width U of the band in which the density change takes place when a sharp edge is being radiographed, Values of U can range from 0·04 mm or less to more than 0·75 mm. depending on conditions.

To reduce unsharpness it is necessary to understand the factors which cause it. *Geometric unsharpness* is due to the finite size of the focal spot and to movement of either source, object or film, whereas *inherent unsharpness* arises from the nature of the emulsion and of the screen when intensifying screens are used.

In section 5.11 reference has already been made to the desirability of using as small a focal spot as possible to lessen unsharpness. Both the cause and the remedy of unsharpness due to movement are so obvious that no discussion is necessary.

Inherent unsharpness is not such a simple matter. In the emulsion, it is due primarily to the photoelectrons liberated when X-ray quanta are absorbed by the silver halide molecules. These electrons, liberated with kinetic energy which is greater the shorter the wave length of the rays (or the higher the kV), are able to render developable halide grains at short distances away from the places where they originated and so cause blur. When salt intensifying screens are used, unsharpness can arise from the finite size of the screen crystals and from the reflection and the diffraction of visible light by such crystals.

From its nature inherent unsharpness cannot be corrected, but by experiment its magnitude under different conditions can be found. As is to be expected from what has been stated in the preceding paragraph, its magnitude increases with increasing kV. For example,

measurements made by Halmshaw* using the same type of film and the same screen, give values of U ranging from 0·55 mm for 200 kV rays to 0·23 for 50 kV. His measurements show also that with the same type of film and the same kV (100), U for a high speed tungstate screen was 0·36 mm, but only 0·19 mm for a fine grain tungstate screen. With a lead foil intensifying screen of thickness 0·002 inch the unsharpness was the same as when the screen was not used.

9.6. Resolution. Definition of an image and the ability to see detail clearly depend on both sharpness and contrast, and for very high resolution, on the fineness of the grains of the emulsion. Resolution is generally expressed by giving the smallest distance two points on an object or an image can be separated and still be seen as two. Under favourable conditions of illumination the unaided eye can separate objects as close as about 150μ or 0·15 mm. When a radiograph is viewed on an illuminated screen by the naked eye this is the limit of resolution. Higher resolution can be obtained by making a photographic enlargement of the radiograph, but only if two conditions are fulfilled. A concrete example will make clear what these conditions are. Suppose one wishes to have a resolution of 1μ, that is, to see details of an object separated by no more than this amount. Whatever the means used to obtain a radiograph, no amount of enlargement will enable the original structure to be seen unless in the radiograph: (*a*) there are two *separated* points on the image corresponding to two points on the object 1μ apart; and (*b*) these separated images do not fall on the same grain of the emulsion. Condition (*b*) means that, if the grain size is of the order of 2μ, the primary radiograph must have a minimum magnification of 2. If the primary magnification M is 2, a further magnification or enlargement of $\frac{150}{2}$ or 75 would be necessary (but impracticable) to bring the separation of the images up to 150μ, the limit of resolution of the eye. If M is 20, the magnification of the second stage need only be 7·5.

As a matter of fact, because of the lack of uniformity in the image arising from the presence of clumps of silver particles, ordinary X-ray films should not be enlarged more than a few times. With too much enlargement background structure is seen. If a resolution of 1μ is desired, the product of M times the degree of enlargement must equal at least 150, as we have seen above, but it should not greatly exceed that value. According to information given the author by

* *Some factors affecting definition in a radiograph*, R. Halmshaw, Report No. 22/51, Armament Research Establishment, 1952.

Dr. W. C. Nixon in connection with the Cosslett and Nixon X-ray microscope discussed in the next section, if, for this resolution, a total magnification of 150 is obtained using $M=15$ and an enlargement of 10, the field of view is much larger than when $M=150$ with an enlargement of 1. For a resolution of $0{\cdot}1\mu$, the combination which gives the best field for an overall magnification of 1,500 is $M=150$ and enlargement $=10$.

9.7. Microradiography. To obtain high resolution equal to or less than 1μ, at least three methods have been used. In this text reference is made to two, each of which is simple in principle. The first consists in making a radiograph of a thin specimen by placing it in *contact* with a fine-grained emulsion and subsequently making a photographic enlargement. Because the specimen is thin and is in contact with the emulsion, focal spots of the order of 1×1 mm may be used. To obtain contrast for thin specimens very soft rays of wave length 1 angstrom or longer must be used. By this method, which has been used with considerable success, notably by Engström of Sweden, a resolution of about $0{\cdot}5\mu$ has been obtained.

At Eindhoven Philips have recently developed miniature X-ray tubes suitable for microradiography by this method, particularly in the field of histo-chemistry. With one of these tubes only a few centimetres long, having a focal spot of 0·3 mm diameter and a beryllium window 50μ thick, a resolution of $0{\cdot}5\mu$ has been obtained. These tubes are operated on voltages in the range 2 to 5 kV.

9.8. The Projection Shadow Microscope. Such success has been obtained by this second method, developed originally at Cambridge by Cosslett and Nixon, that three firms are making commercial prototypes. In this method an enlarged shadow image of a thin specimen O, Fig. 9.2 is formed on a photographic film P by X-rays emerging from an *extremely small* focal spot S. Standard fine grain X-ray films (grain size of the order of $1–2\mu$) can be used because the resolution obtainable depends primarily not on grain size, but on two other factors: (*a*) the smallness of the focal spot; and (*b*) the absence of diffraction effects. By using electron lenses somewhat as in an electron microscope, the electrons emitted by a portion of a heated tungsten filament are concentrated on a spot 1μ or less in diameter. The most elaborate part of the whole instrument is the equipment for obtaining and guiding the electron beam inside an evacuated chamber. The focused beam strikes the target, a piece of tungsten, which is 1μ thick if the spot is 1μ in diameter, supported by a thick washer with a small opening, placed at the far end of the

chamber. The tungsten then acts both as target and window, X-rays emerging from the focal spot *S*. The specimen under examination is placed at *O*, in air at atmospheric pressure, just out-

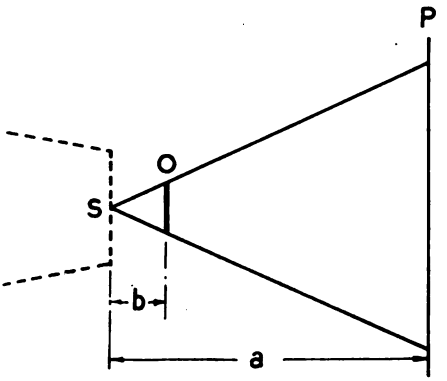


FIG. 9.2. Diagram to illustrate the basic principle of the Cosslett and Nixon projection X-ray shadow microscope. *S* represents the extremely fine focal spot, *O* a small object, *P*, the photographic film.

side the target. By accelerating the electrons by 10 or 12 kV soft rays of suitable wave length are obtained.

Unlike a conventional X-ray tube, no cooling of the target is necessary because with extremely small targets, heat is dissipated rapidly. For a spot of diameter 1μ, for example, on a copper target 1μ thick, a power load of 680 kilowatts per mm²* may be supplied, as compared with a load of 1 kilowatt per mm² in a standard tube of good design.

Effect of diffraction

In optical instruments diffraction, or the spreading out of light waves, is the factor which puts a limit to the resolution obtainable. When X-rays are used, diffraction is less because of their shorter wave lengths. Moreover, with the arrangements of Fig. 9.2, it can be shown that if *b*, the distance of the object *O* from the source *S*, is kept sufficiently small, diffraction is of less importance than the finite size of the focal spot. Cosslett and Nixon state that for a resolution of 1μ, with a wave length of 2·4 angstroms, diffraction is less than 1μ if *b* is less than 4 mm. If the resolution is to be $0{\cdot}1\mu$ (recently obtained) *b* must be less than 40μ or 0·04 mm. Evidently

* The actual load on a spot of diameter 1μ is of course only $680\pi\left(\frac{\cdot 001}{2}\right)^2 \times 10^8$ or 0·53 watt.

for extremely high resolution b is so small that only very thin specimens could be used.

Magnification

A glance at Fig. 9.2 will show that M, the *primary magnification* of the radiograph is equal to $\frac{\text{image distance}}{\text{object distance}} = \frac{a}{b}$. With $b = 1$ mm and a, the " camera length " $= 40$ mm, $M = 40$. Hence, with these dimensions, details of an object 1μ apart would be 40μ apart on the film and so would not be visible by the naked eye without a further magnification or enlargement of at least $\frac{150}{40}$ or about 4 times. Cosslett and Nixon have used values of M ranging from 10 to as high as 1,000. In the photograph reproduced in the frontispiece through the kindness of Cosslett and Nixon, the value of M was 20 and the enlargement factor 7·5. The primary radiograph was taken with a tungsten target 1μ thick, with 10 kV, and an exposure of 5 minutes.

9.9. Tomography. This is the name applied to the technique of obtaining a radiograph which reveals satisfactorily details *in a particular plane* or section of the body, but gives blurred images of adjacent sections. The basic principle, which is quite simple, can be understood by reference to Fig. 9.3. If F_1, F_2, and F_3 represent three

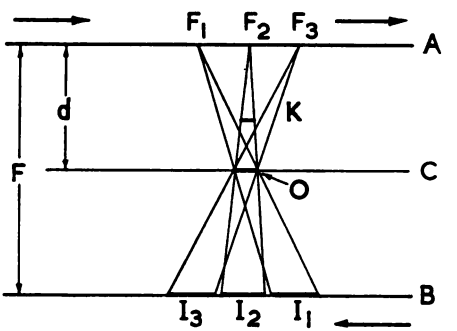


FIG. 9.3. Diagram to illustrate the basic principle of tomography. As the focal spot of an X-ray tube moves from F_1 to F_3 in plane A, the images I_1, I_2 and I_3 of an object O in the plane C are always in the same position on a film moving in the opposite direction in the plane B.

positions of the focal spot of an X-ray tube (or a spot source of light) in the plane A, and I_1, I_2, and I_3 are the corresponding images in the plane B of an object O in the plane C, the size of the image is the same in each case. The magnification, it is easily shown, equals F/d. It follows that, if an X-ray tube and a film are mechanically coupled

so that when the focal spot moves continuously from F_1 to F_3 the film moves simultaneously in the opposite direction, *the image of O will always be in exactly the same position on the film.* On the other hand, it can easily be shown that, if we consider an object such as K in a plane above or below O, its image is in a different place on the film for each position of the focal spot. It follows that there is a blurring of the images for objects in planes other than C.

Watson of Ilford Limited, a pioneer in this field, has shown that this principle can be extended to do multisection radiography, that is, to obtain simultaneously, on say five different films, radiographs of five different sections.

PROBLEMS AND QUESTIONS

1. The brightness of an illuminator (uniformly illuminated) is 500 millilamberts. Find the brightness of an area of a film mounted on the illuminator, if the density of the area is (*a*) 1, (*b*) 2, (*c*) 1·5. *Ans.* (*a*) 50 ; (*b*) 5 ; (*c*) 15·8 millilamberts.

2. The X-ray image of a finger is observed on a fluorescent screen. If the brightness of the light leaving the image of the bone is $\frac{1}{4}$ of that from the surrounding tissue, find the contrast between the image of the bone and the tissue.

Solution : Contrast on a fluorescent screen* is measured by $\log \frac{B_i}{B_s}$, where B_i is the brightness of a spot on the image and B_s is the brightness of the surroundings. Hence, in this problem

$$\text{contrast} = \log 4 = 0{\cdot}6.$$

3. If in question 2 the screen is replaced by a film and a radiograph made, find the contrast between the image of the bone and the surrounding tissue, if the gamma of the developed image is (*a*) 1 ; (*b*) 2.

Solution : Since the brightness of a spot on a fluorescent screen is directly proportional to the intensity of the incident beam of X-rays, it follows that in question 2, the intensity of the X-ray beam leaving the bone must be $\frac{1}{4}$ of that of the beam leaving the tissue. Hence the exposure E_t for the tissue is 4 times E_b, the exposure producing the bone image, since the time is the same for each.

Therefore, applying relation (4) on page 142, we have,

for case *a*, $$\text{contrast} = \gamma \log \frac{E_t}{E_b}$$
$$= 1 \log 4 = 0{\cdot}6,$$

and for case (*b*), $$\text{contrast} = 2 \times 0{\cdot}6 = 1{\cdot}2.$$

4. (*a*) The contrast between the image of a piece of bone and the surrounding tissue as seen on a fluorescent screen is 0·4. Find the ratio of the intensity of the X-ray beam leaving the bone to that leaving the surrounding tissue.

* This should not be confused with contrast sensitivity discussed in section 7.11.

(*b*) The screen is replaced by a film and a radiograph taken, exposure being made at the same kVp. If the gamma of the developed image is 1·5, find the contrast between the bone image and the surroundings when the film is viewed on an illuminator. *Ans.* (*a*) 1 : 2·5. (*b*) 0·6.

5. A radiograph is placed on an illuminator and the intensity of the light emerging from (*a*) the image of a bone and (*b*) the immediate surroundings of the image, is measured. If the ratio is found to be 1 to 30, find the contrast between bone image and its surroundings. *Ans.* 1·5.

6. In problem 5, find the ratio of the intensity of the original X-ray beam after leaving the bone to that of the rays leaving the tissue, if the gamma of the developed image is (*a*) 1 ; (*b*) 2. *Ans.* (*a*) 1 to 30. (*b*) 1 to 5·5.

7. A small flat circular metal plate with very sharp edges is radiographed with distance from focal spot to the plate 30 cm, and from focal spot to film 40 cm. Find the approximate width of the band of variable density (that is, the geometric unsharpness) at the edge of the image, for a focal spot of (*a*) 1 mm diameter ; (*b*) 4 mm diameter. *Ans.* (*a*) 0·33 mm ; (*b*) 1·33 mm.

8. In a tube designed for microradiography, why are the windows frequently made of beryllium?

9. A microradiograph of a thin object is taken on an emulsion with grain size 2μ. Explain why no amount of enlargement would give a resolution smaller than this value.

10. A pin-hole in a lead sheet placed 10 inches from the target of an X-ray tube projects an image of the focal spot on a film placed 30 inches from the target. If the image measures 8×8 mm and the target face is inclined 71° to the axis of the tube, find the true area of the focal spot.

11. The exposure for a certain radiograph taken at 60 kV and with a film-focal spot distance of 40 inches is 60 ma. Estimate the exposure required when 70 kV is used and a film-focal spot distance of 5 feet. Assume an increase in transmission of 20 per cent due to the increased kilovoltage.

12. The part of an X-ray beam which passes through a bone is reduced in intensity 300 per cent more than that passing through the neighbouring tissue. If a radiograph is made on a film whose mean gamma is 4, find the contrast between the image of the bone and its surroundings.

13. Compare the intensities in air of X-rays produced by the same tube under the following conditions :

(*a*) 60 kV, 5 ma, 30 cm from target.

(*b*) 80 kV, 10 ma, 40 cm from target.

CHAPTER X

SECONDARY X-RAYS AND ABSORPTION

10.1. Secondary X-rays. In this chapter we discuss in detail what happens when a beam of X-rays is reduced in intensity by passage through an absorbing layer. Suppose we arrange an X-ray tube and an electroscope, as in Fig. 10.1, so that no part of the *primary* beam leaving the target can enter the window of the electroscope. On operating the tube we find that the leaf falls very slowly. If, however, a block of wood, R, is placed in the path of the primary beam, the electroscope is discharged more quickly. This increased ionization is due to the emission by the wood of what are called *secondary* X-rays. The experiment illustrates the important principle that, whenever X-rays fall on matter, there is a re-emission in all directions, of secondary X-rays. This fact must never be forgotten. To stand out of the direct path of a beam of X-rays by no means insures protection from them, for we may be bathed in rays from objects against which the primary beam strikes.

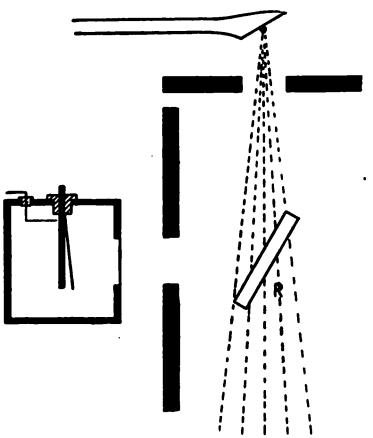


FIG. 10.1. Experimental arrangement to show existence of secondary X-rays.

Investigations regarding the nature of secondary X-rays show that there are in general two kinds: (1) *scattered* rays, which in general consist of two components, one whose wave length is the same as the primary beam, the other whose wave length is longer; (2) *characteristic fluorescent* rays which are characteristic of the material of the radiator, being in fact identical with the characteristic X-rays emitted by the same material when used as the target of an X-ray tube.

10.2. Scattered Radiation. We note certain details of importance in radiology.

(1) Scattered rays are emitted in all directions (even backwards) by the radiator, but with a maximum intensity in the forward direction, that is, in the same direction as the primary beam. The shorter the wave length the greater the intensity scattered in the forward direction.

(2) *For elements of low atomic weight and a primary beam of short wave length, say not exceeding* 0·25 *angstrom, scattered radiation is of greater importance than characteristic.* Since tissue is made up almost entirely of the light elements hydrogen, carbon, oxygen, and nitrogen, this means that when a beam of short wave length traverses tissue, scattered rays are of very great importance. Further reference will be made to this question.

(3) When scattered rays were first studied, it was considered that their wave length was exactly the same as that of the primary beam. Further experiments, however, particularly those of J. A. Gray and A. H. Compton, show that the scattered beam consists of a mixture of *unmodified* rays, that is, those whose wave length is the same as that of the primary beam, and *modified* rays, those whose wave length is different. *For light elements and a primary beam of short wave length the intensity of the modified beam is relatively much greater than that of the unmodified, a fact which means that there is a progressive softening of a beam, or lengthening of wave length, when it traverses tissue.*

The magnitude of this change in wave length depends on the direction in which the scattered rays are being observed. If ϕ is the angle the scattered beam under observation makes with the primary beam, Compton showed that $\Delta\lambda$, the change in wave length, is given by the relation

$$\Delta\lambda = 0{\cdot}0243\ (1 - \cos\phi) \text{ angstrom.}$$

Thus, for $\phi = 90°$, the change is 0·0243 angstrom; for $\phi = 180°$, the change is 0·0486 angstrom. Hence, for a primary beam of wave length 0·2 angstrom, the scattered beam observed in a direction at right angles to the primary, has a wave length 0·2243 angstrom. If the primary beam is of very short wave length, 0·05 for example, the percentage change in the wave length of the scattered rays is considerable, this wave length being changed to 0·0743 at 90° and 0·0986 at 180°.

The reason for this change in wave length is given in section 10.6.

10.3. Characteristic Radiation. (1) As already noted, fluorescent characteristic rays are identical with the characteristic rays previously discussed (section 8.7), the difference between the two being solely in their mode of generation. Fluorescent rays result from the

stimulus of an exciting primary beam of X-rays, not from the impact of electrons against a target.

(2) To excite fluorescent rays of the *K* group the wave length of the primary beam must be shorter than that of any of the characteristic rays in this group. Since the shortest wave length emitted by any of the first 35 elements in the periodic table is longer than 1 angstrom, and for elements with atomic numbers between 35 and 63 exceeds 0·3 angstrom, this condition is generally fulfilled for beams utilized in radiology, at any rate for all elements except those of high atomic weight. To excite the *K* characteristic rays of an element like tungsten, however, a primary wave length shorter than 0·18 is necessary; for platinum, shorter than 0·16; and for lead, shorter than 0·14 angstrom.

In this connection an important point relating to filtration arises. Suppose a primary beam contains a mixture of hard and of soft rays and that a filter of copper is used to remove the soft components. In traversing the copper, the hard primary rays will excite the characteristic rays of copper and hence these will emerge from the filter as well as a portion of the original hard beam. Now characteristic rays of copper are soft and may give rise to the injurious effect which the filter is put in to prevent. A second substance, aluminium for example, whose characteristic rays are still softer than copper, should then be used on the side of the copper remote from the tube. This substance will then absorb the soft secondary rays of copper, but its own characteristic rays will do no harm because they are so much longer than those of copper that even a short thickness of air absorbs them.

(3) *Relative to scattered radiation*, characteristic becomes more important *for longer wave lengths*. In tissue, for example, to quote from Mayneord " for $\lambda = 0{\cdot}2$ angstrom, the absorption is 90 per cent scatter and 10 per cent fluorescent absorption, while at 1 angstrom, some 18 per cent only is due to scatter ". Since the wave lengths utilized in deep therapy are often even shorter than 0·2 angstrom, we see again the importance of scattered radiation in therapy.

For elements of high atomic weight, especially for longer wave lengths, absorption due to the excitation of characteristic rays is of greater importance than that due to scattered radiation.

Further details about characteristic wave lengths and scattered radiation are given later in this chapter.

10.4. Photoelectrons. When the wave length of the primary beam is short enough to excite characteristic rays, there is a photo-

electric emission of electrons by the radiator. These electrons are of very great importance because part of the ionization caused by a beam of X-rays is due to them. What happens is this. A quantum of the incident primary radiation (if the wave length is short enough) has enough energy to eject an electron from the K shell of an atom of the radiator; or, alternately, a somewhat longer wave length may remove an electron from the L shell; or a still longer wave length, from the N shell. In radiology, we are chiefly concerned with the removal from the K shell. After the removal of the electron, characteristic rays are emitted in the way already described in section 8.10. When the incident quantum has more than enough energy to remove the electron, the excess energy goes into the kinetic energy of the electron. In general, therefore, the ejected photoelectron has sufficient velocity to ionize atoms by collision. This fact is of very great importance because it is the ionization produced in tissue which is responsible for any biological effects caused by X-rays.

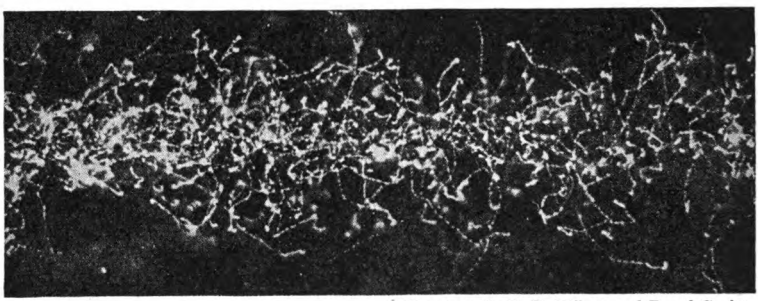
If, however, the primary beam consists of extremely short wave lengths with corresponding quanta of high energy which are greatly in excess of the amount necessary to remove an electron, the chance of its removal is less than for longer wave lengths. (See section 10.9.)

The photoelectrons released by visible and ultra-violet light (section 7.12) are essentially the same as those discussed in this section. They however originate in the outer parts of an atom where the electrons are so loosely bound that quanta of low energy, of only a few electron-volts, can liberate them. Compare such a value with the 29,300 electron-volts necessary to remove a K electron from a tin atom. (See section 10.9.)

10.5. Seeing Ions. The ionization of a gas traversed by a beam of X-rays is very beautifully illustrated in Fig. 10.2, an example of what is sometimes called a cloud expansion chamber or cloud-track photograph. As we shall have other occasions where we wish to visualize the presence of ions, the basic principles employed in taking a photograph like this should be understood. Although we cannot see an ion any more than an electron, it is possible by a very beautiful experiment, first performed by C. T. R. Wilson at Cambridge University, to make each ion the centre of a little drop of water which reveals its presence in unmistakable fashion.

The idea on which the experiment is based is really a very simple one. When air is laden with moisture, a fog will form much more readily if dust is present than if the air is dust-free. If all the sooty

smoke which pollutes the air over the city of London could be consumed or in some way prevented from leaving chimneys, fogs would be neither thicker nor more prevalent over that city than elsewhere in



Courtesy C. T. R. Wilson and Royal Society

FIG. 10.2. A cloud-track photograph showing paths of photoelectrons when a beam of X-rays traverses a gas.

England. This is nothing but sound physics, because water condenses readily when little particles of dust or dirt are present to act as nuclei around which drops can form. Now Wilson showed that *ions also act as nuclei for the formation of water drops*. In the actual experimental arrangement ions are formed by an ionizing agent in moisture-laden, but dust-free air, the air is allowed to expand suddenly, and thereby be cooled, water condenses on the ions, and a flash of light enables a photograph to be taken. *For each invisible ion, a visible* drop appears.

In Fig. 10.2, then, each little white dot represents a droplet of water and hence an ion. The student should have no difficulty in tracing the irregular paths of some of the photoelectrons since they mark their trails by the ions they have formed.

Another method of revealing the track of an ionizing particle is described in section 14.11.

10.6. Recoil Electrons and Scattering. To obtain characteristic rays a photoelectron must be ejected from the atom. Scattered rays, on the other hand, arise from the impact of the primary beam against an electron which is comparatively free, that is, an electron not strongly held by the attraction of the nucleus of an atom. To explain the change in wave length which takes place on scattering, it is necessary to think of X-rays as having a corpuscular as well as a wave nature. Phenomena of interference have given ample evidence that ordinary light, X-rays—in fact, all electromagnetic radiations—have a wave nature. On the other hand, it is often necessary to

interpret facts by thinking of radiation as concentrated in little bundles called *photons*, each photon possessing the quantum of energy, which we have seen in section 8.10, is equal to Planck's constant h multiplied by ν, the frequency.

Now Compton showed that the observed change in wave length when a primary beam is scattered can be readily explained if we treat the impact of a photon against the scattering electron in much the same way as the collision of two particles. By applying the ordinary laws of conservation of energy and of momentum, he showed that if a photon with energy equal to $h\nu$ strikes an electron (see Fig. 10.3), the photon goes off in direction ϕ as scattered radiation with energy $h\nu'$. where ν' is less than ν, while, at the same time, the electron goes off in direction θ, with initial energy equal to the difference between $h\nu$ and $h\nu'$. This electron, usually called a *recoil* electron, may cause some ionization, although sometimes much less than that of a photoelectron. In some cloud-track photographs, the ionizing paths due to recoil electrons may readily be observed.

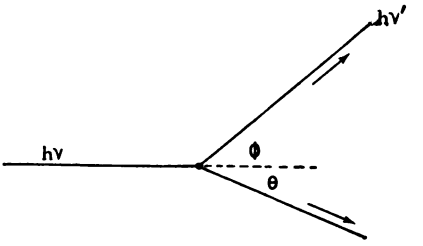


FIG. 10.3. An incident photon on striking a free electron is scattered in direction ϕ as a photon of longer wave length and the electron goes off in direction θ.

When a large number of scattering collisions take place, there are many different values of ϕ, with corresponding values of θ.

As shorter and shorter wave lengths are used, recoil electrons have more and more energy. Since, as we have noted in section 10.3, extremely short wave lengths cause comparatively little emission of photoelectrons (especially in materials of low atomic weight), it follows that for such wave lengths, the ionization in a medium like tissue is almost entirely due to recoil electrons. Stated otherwise, the ionization in tissue caused by X-rays generated by potential differences exceeding, say, 200,000 volts, is more and more due to recoil than to photoelectrons, as the voltage gets higher and higher. It further should be noted also that because of its nature, the Compton effect is not dependent on Z, the atomic number of the absorbing atoms. It follows that wave lengths (generated at lower voltages) which are photoelectrically absorbed, where the absorption depends very much on the value of Z, are much more suitable for diagnostic purposes.

At potentials of the order of a few million volts, the phenomenon of pair production becomes important. (See section 10.7.)

10.7. Nature of Absorption. We are now in a position to examine a little more carefully the reason why an incident beam of X-rays is reduced in intensity when passing through an absorbing layer. This reduction in intensity is due to one or more of the following causes.

(1) A *true* absorption, when some of the energy of the incident beam is expended in the production of photoelectrons. For each photoelectron liberated, one photon disappears, its quantum of energy being expended in removing the electron.

(2) An *apparent* absorption due to scattering. It is necessary to distinguish two types of scattering: (*a*) without emission of recoil electrons; (*b*) with associated emission of recoil electrons.

In case (*a*) the photons undergoing scattering are diverted out of their original paths *with no loss of energy*, and consequently with no change in wave length. The intensity of the original beam is reduced, therefore, not because any of the original energy is truly absorbed, but because most of the scattered photons are deflected out of the path of the primary beam.

In case (*b*), a photon which is scattered gives up part of its quantum of energy to a recoil electron and consequently is diverted out of the original path as a photon of less energy, or of longer wave length. Hence the portion of the energy of the original photon which is communicated to the electron is truly absorbed.

(3) *Pair Production.* This phenomenon, which can occur only when the energy of an incident photon exceeds 1·02 MeV, is discussed in section 15.6 and for the present need not concern us.

When absorption is dealt with quantitatively by the use of coefficients (see section 10.10), frequently a separate coefficient is used for each process. Thus, the symbol τ is used as the photoelectric coefficient, σ, the scattering coefficient, subdivided into σ_s for true scattering, σ_a for absorption due to recoil electrons and π for pair production.

As will be evident from the preceding sections in this chapter, the relative importance of the various processes, and hence the numerical values of the coefficients, depend both on the nature of the absorbing material and the wave length of the primary beam of X-rays. For elements of low atomic weight, which are of special importance to the radiologist, and for short wave lengths or hard X-rays, such as are developed by voltages exceeding say 200,000 volts, photoelectric

absorption is small or negligible. For long wave lengths or soft rays, generated by potential differences of 50,000 volts or less, photoelectric absorption is the more important for light elements.

TABLE XVII

Element	λ	Photons			Electrons	
		incident	emergent	scattered	photo	recoil*
Carbon -	0·1	2,000	1,936	63	1	63
	0·7	2,000	1,740	80	180	50
Aluminium	0·1	2,000	1,917	74	9	74
	0·7	2,000	491	105	1,404	40
Copper -	0·1	2,000	1,498	296	206	290
	0·7	2,000	0	455	1,545	15

The numbers given in Table XVII will give some idea of the relative importance of the various processes in the elements carbon, aluminium, and copper, for the two wave lengths 0·1 angstrom and 0·7 angstrom. In obtaining these numbers, a beam of X-rays containing 2,000 photons is assumed to be incident on 1 cm^2 of a piece of absorbing material 1 mm thick (actually the number of photons would be much greater than this) and, by the use of absorption coefficients, a calculation is made of the number of photons emerging in the transmitted primary beam, the number deflected out of the beam by scattering, and the number absorbed in the production of photoelectrons. What is of importance is not the actual values of the various numbers but their relative values.

It should not be forgotten that a scattered photon may be rescattered, with progressive lengthening of wave length, if recoil electrons are generated at each scattering; that in some cases a scattered photon of lengthened wave length may be completely absorbed liberating a photoelectron; that the photons associated with characteristic rays may also undergo scattering, the whole process, especially in a large mass of tissue, being far from simple.

10.8. Filtration and Critical Absorption Wave Length. Reference has frequently been made to the use of filters for removing the softer components of a beam and it has been stated that, generally speaking, shorter wave lengths are more penetrating than longer. This statement we must now examine a little more carefully.

* The numbers in this column, especially those relating to $\lambda = 0{\cdot}7$, are very rough approximations estimated from data given on pp. 122 and 214, *X-rays in Theory and Experiment*, Compton and Allison, D. Van Nostrand Company, 1935.

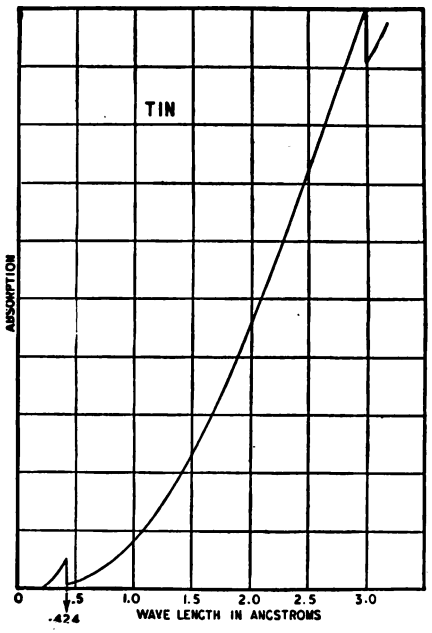


FIG. 10.4. Graph showing change in absorption of tin with changing wave lengths.

For a given absorbing substance, it is only partially true to state that the longer the wave length, the greater the absorption. When absorption measurements are made over a wide range of wave lengths, it is found that as the wave length is increased, at certain critical wave lengths, the absorption suddenly falls from a high to a low value. As a first illustration consider the element tin and the graph of Fig. 10.4, which shows how the absorption for a fixed thickness of this element changes with changing wave length. On the horizontal axis of the graph, the wave length scale is in angstroms, but the scale for absorption on the other axis gives only relative values. Starting with wave length shorter than 0·1 angstrom we note that at first tin is extremely transparent, but that gradually the absorption increases until the wave length 0·424 is reached. At this critical value, a sudden drop in the absorption takes place, wave lengths just longer than 0·424 being transmitted much more readily than those just shorter. However, as the wave length continues to increase, the absorption again steadily increases until at approximately 3 angstroms, there is another sudden decrease. The qualifying word "approximately" is used, because actually there are three sudden changes, at 2·77, 2·97 and 3·15 angstroms.

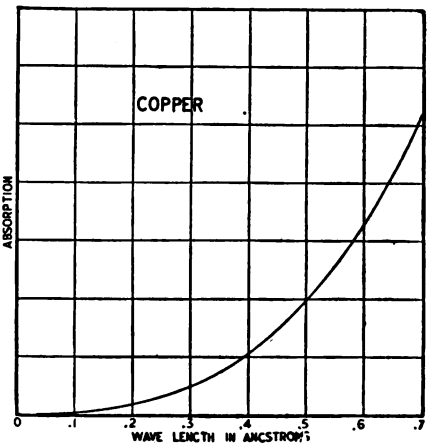


FIG. 10.5. Graph showing change in absorption of copper with changing wave lengths.

The same general phenomenon occurs if tin is replaced by copper, except that the first sudden decrease in absorption does not take place until the wave length 1·38 angstrom is reached. In the graph Fig. 10.5, the change in the absorption of copper for wave lengths as long as 0·7 angstrom is plotted. Contrast this graph with that of Fig. 10.6, which applies to lead. Note that for lead, the value of the

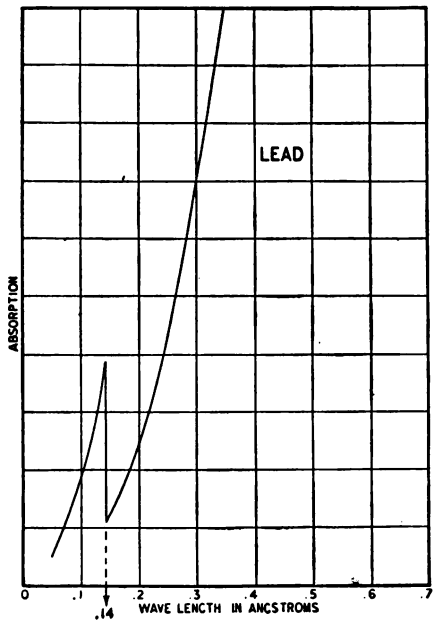


FIG. 10.6. Graph showing change in absorption of lead with changing wave lengths.

first critical absorption wave length is 0·14 angstrom, a wave length right in the middle of the region used in deep therapy. It follows that a filter of lead is very undesirable, because of the high absorption of some of the very wave lengths which the operator wishes to use, that is, those just shorter than 0·14 angstrom.

In choosing a filter, therefore, care must be exercised that there is no critical absorption wave length in the region in which the wave lengths are wanted. A glance at the values of the shortest (or *K*) critical absorption wave lengths given in Table XVIII, will show that, for the ordinary materials which may conveniently be used as filters, with the exception of lead (platinum and tungsten cannot be classed as ordinary materials), the critical absorption wave length is

considerably longer than the longest wave lengths usually used in radiology. For all these elements, if we restrict ourselves to radiology uses, the shorter the wave length, the more penetrating the beam.

10.9. The Meaning of Critical Absorption Wave Lengths. In section 8.10 we stated that in order to have an emission of characteristic fluorescent rays, the incident photon must have enough energy to remove an electron from the K or the L or the M shells. The energy of the photon is absorbed and used to do the work of removing the electron. We have also previously pointed out that the quantum of energy possessed by a photon has the magnitude $h\nu$, where h is Planck's constant and ν is the frequency of the X-ray. Suppose now, we begin our absorbing experiments with an element like tin, using first a wave length as short as 0·05 angstrom. The corresponding frequency is then extremely high (since the shorter the wave length the higher the frequency), and the quantum of energy possessed by the photon is far more than is necessary to remove a K electron. This photon is then not readily absorbed because we know from experiments dealing with energy exchanges of this kind that the probability of an absorption with consequent ejection of the electron is greater, the more nearly the energy possessed by the photon is equal to the energy needed to remove the electron. Now as the wave length of the primary beam is gradually increased, or the frequency decreased, the energy possessed by the photon becomes less and less until at a certain critical wave length, 0·424 for tin, it is exactly equal to the amount needed to remove the

TABLE XVIII—SHORTEST OR K CRITICAL ABSORPTION WAVE LENGTHS FOR A FEW COMMON ELEMENTS

Atomic Number	Element	Critical Wave Lengths
13	Aluminium	7·93 angstrom
26	Iron	1·74
28	Nickel	1·48
29	Copper	1·38
30	Zinc	1·28
47	Silver	0·485
50	Tin	0·424
74	Tungsten	0·178
78	Platinum	0·158
82	Lead	0·140

K electron. At that stage absorption becomes a maximum. For all wave lengths longer than this critical value, the photon has not

enough energy to remove a K electron, and at first there is a marked decrease in absorption since the photons in this region have far more than enough energy to remove an L electron. But once more as the wave length increases, the absorption gradually increases again until it reaches a maximum at a second critical value, where the energy of the photon is exactly that required to remove the L electron. Because an electron can be removed from each of the L subshells, there are the three critical absorption L values to which reference has already been made.

It is interesting to note that, if we take the K critical absorption wave length, 0·424, and calculate the corresponding voltage by means of the relation

$$\text{maximum voltage} = \frac{12{\cdot}4 \times 10^3}{\text{wave length in angstroms}}$$

the value we obtain, 29·1 kV, is exactly equal to the voltage which must be applied across an X-ray tube with a tin target before the characteristic rays of this element are emitted. This agreement is due to the fact that, whether we excite the complete X-ray spectrum by the impact of electrons against a target, or by the absorption of a primary beam, the atom must be ionized by the removal of a K electron. In the latter case the energy utilized is that of the incident photon which, as we have already emphasized, depends on the wave length; in the former case, the energy is that acquired by an electron in falling through the potential difference across the tube. The two energies must be equal and that is the cause of the agreement between the values of the voltage calculated by means of the above relation and the experimental value found necessary to excite the characteristic rays. Indeed, it is not a difficult matter to derive the above relation connecting voltage and wave length, if we equate these two energies.

If the student will refer back to page 45, he will be able to write down at once that the energy acquired by an electron after falling through V volts is equal to

$$V \times 1{\cdot}6 \times 10^{-12} \text{ ergs.} \qquad (1)$$

Again, the energy possessed by a photon

$$= h\nu$$

$$= h\frac{c}{\lambda}, \text{ since frequency} = \frac{\text{velocity of waves}}{\text{wave length}},$$

$$= \frac{6{\cdot}62 \times 10^{-27} \times 3 \times 10^{10}*}{\lambda \text{ (in centimetres)}} \text{ ergs},$$

$$= \frac{19{\cdot}86 \times 10^{-17}}{\lambda \text{ (in angstroms)} \times 10^{-8}},$$

$$= \frac{19{\cdot}86 \times 10^{-9}}{\lambda \text{ (in angstroms)}}. \qquad (2)$$

Equating (1) and (2), we have

$$V \times 1{\cdot}6 \times 10^{-12} = \frac{19{\cdot}86 \times 10^{-9}}{\lambda \text{ (in angstroms)}}$$

or

$$V \text{ (in volts)} = \frac{12{\cdot}4 \times 10^{3}}{\lambda \text{ (in angstroms)}}.$$

10.10. Absorption Coefficients. In section 7.10, it was pointed out that when a homogeneous beam is reduced in intensity by passage through absorbing layers, equal thicknesses reduce the intensity by the same *fractional* amount; or, alternately, equal thicknesses reduce the logarithm of the intensity by equal amounts. When absorption is studied quantitatively, these ideas are utilized by adopting absorption coefficients.

The *linear absorption coefficient*, represented by μ, is, by definition, equal to the reduction, per unit thickness, in the logarithm (to the base e) of the intensity. Students who have studied logarithms will perhaps recall that the natural base, that is, the base which is used in the calculation of the actual numerical values found in log tables, is not 10, the common base, but the number e, numerically equal to 2·7183. According to our definitition, then

$$\mu = \frac{\log_e I_0 - \log_e I}{x}$$

where I_0 is the original intensity and I the intensity after the beam has traversed a thickness equal to x cm of the absorber.

To be of practical use, that is, in order that log tables may be used, we must change over to the base 10. When this is done, the factor 2·30 appears in the working formula

$$\mu = \frac{2{\cdot}30\,(\log_{10} I_0 - \log_{10} I)}{x}$$

*$h = 6{\cdot}62 \times 10^{-27}$ ergs × sec; the velocity of all electromagnetic waves $= 3 \times 10^{10}$ cm per sec.

$$= \frac{2{\cdot}30}{x} \log_{10} \left(\frac{I_0}{I} \right). \qquad (3)$$

A concrete example will illustrate the use of this relation. Suppose we wish to find μ, for copper, for the particular wave length which is absorbed in accordance with the results given in Table XIII, section 7.10. From this table we note that the intensity falls from an initial $I_0 = 100$ units to $I = 66{\cdot}8$ units after the beam has traversed 0·50 mm of copper. We have, then,

$$\mu = \frac{2{\cdot}30 \, (\log 100 - \log 66{\cdot}8)}{0{\cdot}05}$$

$$= \frac{2{\cdot}30 \, (2{\cdot}0000 - 1{\cdot}8248)}{0{\cdot}05}$$

$$= 8{\cdot}06 \text{ cm}^{-1}.$$

Again, using a thickness of 1 mm, with $I_0 = 100$ and $I = 44{\cdot}7$, we obtain

$$\mu = \frac{2{\cdot}30 \, (\log 100 - \log 44{\cdot}7)}{0{\cdot}1}$$

$$= 8{\cdot}04 \text{ cm}^{-1}.$$

Or, taking one other example, since, when the thickness of absorber changes from 1·00 mm to 1·75 mm, the intensity drops from 44·7 units to 24·5 units,

$$\mu = \frac{2{\cdot}30 \, (\log 44{\cdot}7 - \log 24{\cdot}5)}{0{\cdot}175 - 0{\cdot}100}$$

$$= 8{\cdot}01 \text{ cm}^{-1}.$$

The homogeneous beam of rays to which the results of Table XIII apply, has, therefore, a linear absorption coefficient in copper of 8·0 cm^{-1}, and by this number its quality may be accurately described.

Linear absorption coefficient and h.v.l.

If h = the h.v.l. of a medium for a homogenous beam, then

$$\mu = \frac{2{\cdot}30 \, (\log 100 - \log 50)}{h}$$

$$= \frac{0{\cdot}69}{h}. \qquad (4)$$

10.11. Linear Absorption Coefficient and Exponential Law. Instead of using relation (3), we may use the following exponential expression which is its exact equivalent

$$I = I_0 e^{-\mu x}. \qquad (5)$$

For example, using the data given above that 0·05 cm copper reduces the intensity from 100 to 66·8 units, we can write

$$66{\cdot}8 = 100e^{-0{\cdot}05\mu}$$

or $$e^{-0{\cdot}05\mu} = 0{\cdot}668.$$

From exponential tables μ can then be found.

Students are advised however to use logarithms and relation (3).

10.12. Alternative Definition of Linear Absorption Coefficient. *If x is very small,* relation (5) may be written

$$I = I_0(1 - \mu x), \tag{6}$$

or $$\frac{1}{x} \cdot \frac{I_0 - I}{I_0} = \mu,$$

that is, $$\frac{\text{decrease in intensity}}{\text{increase in thickness}} \times \frac{1}{\text{initial intensity}} = \mu$$

or $$\frac{\text{rate at which the intensity decreases}^*}{\text{initial intensity}} = \mu.$$

Hence, μ is sometimes defined as the ratio of the rate of decrease in intensity, for an area of very small thickness, to the actual intensity at that area.

10.13. Effective Absorption Coefficient. So far we have been considering a homogenous beam. For a heterogeneous beam in which some wave lengths are absorbed more than others, the coefficient obtained by using relation (3) is called the *effective absorption coefficient.* Its value will vary with the thickness of the absorber, as has already been pointed out indirectly in part (2) of section 8.12.

10.14. Mass Absorption Coefficient. Of greater importance than μ, is the *mass absorption coefficient.* Suppose we compare the absorption of a homogeneous beam by water in the liquid state with the same substance in the vapour state. If we keep the cross-section of our beam constant, we find that in order to obtain equal absorption by vapour and by liquid, such a thickness of vapour must be used that the total *mass* of water is the same as in the equivalent thickness of liquid. This suggests that a coefficient more fundamental than μ is one in which we deal with *the reduction in intensity per unit mass, for a beam of unit cross-section.*

$$\begin{aligned}\text{Now mass} &= \text{volume} \times \text{density} \\ &= \text{cross-sectional area} \times \text{length} \times \text{density} \\ &= 1 \,.\, x \,,\, \rho,\end{aligned}$$

for a beam of unit cross-section, length x cm, and density ρ grams per c.c.

From our definition, then, we can write

*In the notation of calculus, this is written $\frac{1}{I}\frac{dI}{dx} = \mu$.

$$\text{mass absorption coefficient} = \frac{2{\cdot}30\,(\log I_0 - \log I)}{\text{total mass}}$$

$$= \frac{2{\cdot}30\,(\log I_0 - \log I)}{x \,.\, \rho}$$

$$= \frac{\mu}{\rho} \text{ cm}^2 \text{ per gm.}$$

For the radiation dealt with above, that is, the beam which has a linear absorption coefficient in copper of 8·0 cm^{-1}, the mass absorption coefficient, or $\frac{\mu}{\rho} = \frac{8{\cdot}0}{8{\cdot}9}$ or 0·90 cm^2 per gm, since the density of copper is 8·9 grams per c.c.

10.15. A Numerical Example. *Given a copper plate of thickness 2·2 mm, find how much it will reduce the intensity of a monochromatic beam of X-rays of wave length 0·2 angstrom, if* $\frac{\mu}{\rho}$ *for this wave length is equal to 1·59 cm² per gm.*

Since $\frac{\mu}{\rho} = 1{\cdot}59$ and ρ for copper $= 8{\cdot}9$ (gm per c.c.),

therefore $$\mu = 1{\cdot}59 \times 8{\cdot}9$$

$$= 14{\cdot}1 \text{ cm}^{-1}.$$

Let I_0 = the intensity of the beam incident on the copper plate, and I = the emergent intensity.

Then, $$\mu = 2{\cdot}30 \frac{\log I_0 - \log I}{x}$$

or $$14{\cdot}1 = 2{\cdot}30 \frac{\log I_0 - \log I}{0{\cdot}22}.$$

Therefore, $$\log I_0 - \log I = \frac{14{\cdot}1 \times 0{\cdot}22}{2{\cdot}30} = 1{\cdot}35$$

or $$\log \frac{I_0}{I} = 1{\cdot}35.$$

Using log tables, we find that

$$\frac{I_0}{I} = 22, \quad \text{or} \quad I = 0{\cdot}045 I_0,$$

that is, the emergent intensity is only about 4·5 per cent of the incident.

Using exponentials, we have the following alternative solution.

$$\mu = \frac{\log I_0 - \log I}{x},$$

can be written

$$\frac{I}{I_0} = e^{-\mu x},$$

or, in this problem,

$$\frac{I}{I_0} = e^{-14 \cdot 1 \times 0 \cdot 22}$$

$$= e^{-3 \cdot 10}.$$

From exponential tables, we find, as before, that $I = 0 \cdot 045 I_0$.

10.16. The Coefficients σ and τ. As we have explained in section 10.7, absorption for wave lengths longer than those corresponding to a million volts is due to the two processes, scattering and photoelectric emission. Accordingly, the coefficient μ is frequently separated into a scattering coefficient σ and a photoelectric coefficient τ. If we use mass absorption coefficients, we can write

$$\frac{\mu}{\rho} = \frac{\sigma}{\rho} + \frac{\tau}{\rho}.$$

As we have noted in section 10.7, σ is sub-divided into two components, σ_s due to the apparent absorption arising from scattering and σ_a due to true absorption by recoil electrons.

Table XIX gives a few values* of $\frac{\sigma}{\rho}$, for four substances and for four wave lengths (in angstroms). A glance at these numbers will show the following.

TABLE XIX

VALUES OF $\frac{\sigma}{\rho}$ FOR FOUR WAVE LENGTHS FOR A FEW SUBSTANCES

Wave Length -	0·1011	0·2022	0·4044	0·8088
Air - - -	0·141	0·164	0·178†	0·189
Wet Tissue -	0·155	0·179	0·196	0·208
Carbon - -	0·141	0·164	0·178	0·189
Iron - -	0·131	0·153	0·167	0·176

* Values are worked out from data in *Actions of Radiations on Living Cells*, D. E. Lea (Cambridge Univ. Press).

† $\frac{\sigma}{\rho} = 0 \cdot 178$ is made up of $\frac{\sigma_s}{\rho} = 0 \cdot 169$ plus $\frac{\sigma_a}{\rho} = 0 \cdot 0094$.

(1) For these wave lengths which are less than 1 angstrom, the differences in the values of the coefficients for these substances are not great.

(2) For a given substance, there is a slow increase in the value of $\frac{\sigma}{\rho}$ as the wave length increases.

TABLE XX—A FEW VALUES OF $\frac{\tau}{\rho}$.

Wave Length -	0·1	0·2	0·4	0·8
Air - - -	0·0024	0·0192	0·147	1·27
Wet Tissue -	0·0024	0·0193	0·145	1·29
Carbon - -	0·0012	0·0085	0·066	0·585
Iron - -	0·142	1·02	7·34	53·7

(3) In the therapy region of wave lengths from 0·1A to 0·2A the values for these different substances range only from 0·14 to 0·18.

The situation is very different when we consider values of $\frac{\tau}{\rho}$. As the numbers in Table XX show, values of this coefficient increase rapidly with increasing wave length. They also increase rapidly with increasing atomic number. Note, for example, the large increase in $\frac{\tau}{\rho}$ for any of the above wave lengths as we go from carbon ($Z=6$) to iron ($Z=26$). For heavy elements and long wave lengths, values of $\frac{\tau}{\rho}$ run into large numbers. This is to be expected because, for wave lengths less than 1 angstrom, $\frac{\tau}{\rho}$ is approximately proportional to $\lambda^3 Z^4$.

For light elements, if we deal with wave lengths much longer than those encountered in deep therapy, values of $\frac{\tau}{\rho}$ are considerably greater than $\frac{\sigma}{\rho}$. On the other hand, for very short wave lengths, $\frac{\sigma}{\rho}$

becomes the more important. For these wave lengths the small value of λ^3 (note that for $\lambda=0{\cdot}1$, $\lambda^3=0{\cdot}001$) makes $\frac{\tau}{\rho}$ small for low values of Z.

If we deal with a sufficiently large range of wave lengths, because of the sudden changes in absorption at the critical absorption wave lengths (section 10.8), there are corresponding sudden changes in both $\frac{\mu}{\rho}$ and $\frac{\tau}{\rho}$. The graphs of Figs. 10.4, 10.5, and 10.6 were plotted from values of $\frac{\mu}{\rho}$ given in Compton and Allison's book.

From the above it should be evident why, in order to obtain radiographs with good contrast, which depends primarily on differences in absorption, fairly long wave lengths (low kilovoltages) are necessary.

10.17. Atomic Absorption Coefficient. Sometimes we are concerned with the absorption per atom and hence we have atomic absorption coefficients, designated ${}_a\mu$, ${}_a\sigma$, and ${}_a\tau$. To evaluate atomic coefficients for a given substance and given wave length, all that is necessary is to divide mass absorption coefficients by the number of atoms per gram.* For example, if we take carbon and wave length 0·2022A, since $\frac{\sigma}{\rho}$ as shown in Table XIX $=0{\cdot}164$, we have

$$ {}_a\sigma=\frac{0{\cdot}164}{\frac{6{\cdot}02\times10^{23}}{12}}=3{\cdot}28\times10^{-24}\ \text{cm}^2. $$

Note that the number of atoms in a gram-atom of an element is $6{\cdot}02\times10^{23}$ (*Avogadro's number*) and the atomic weight of carbon is 12.

10.18. Electronic Absorption Coefficient. Similarly we sometimes are interested in the absorption per electron and the electronic absorption coefficient ${}_e\mu$, ${}_e\sigma_s$, ${}_e\sigma_a$ and ${}_e\tau$. To evaluate these coefficients, we divide the mass absorption coefficients by the number of electrons in 1 gram. Again using carbon as an example and wave length 0·2022, we find, since each atom of carbon ($Z=6$) has 6 electrons

* For the coefficient ${}_a\mu$, this is the same as dividing the linear coefficient by the number of atoms per c.c. Thus

$$ {}_a\mu=\frac{\mu}{\text{no. of atoms per c.c.}} $$

$$_e\sigma^* = \frac{3{\cdot}28 \times 10^{-24}}{6} = 5{\cdot}45 \times 10^{-25} \text{ cm}^2.$$

10.19. The Meaning of Cross-Section. In any of the absorption processes we have been considering, an incident photon interacts with a single atom or electron. For a particular process to take place, the photon must approach sufficiently near the atom or electron. Putting it in another way, we may say that the atom or electron presents a certain target area within which the photon must strike or pass for the process to take place. This target area, which is called the *cross-section* for the particular process under consideration, is of great importance in atomic physics. The unit, called 1 *barn*, is equal to 10^{-24} cm^2 and the usual symbol is σ. In this text, to avoid confusion with the scattering coefficient, we shall use s.

The magnitude of the cross-section for a particular process involving atoms is equal to the atomic absorption coefficient (or electronic coefficient for an electron.) (The proof of this, which may be omitted, is given below.) Thus, the cross-section of carbon, for $\lambda = 0{\cdot}2$, for scattering processes (not separated) $= 3{\cdot}28 \times 10^{-24}$ cm^2 $= 3{\cdot}28$ barn.

Proof that the cross-section for photon absorption by atoms is equal to the corresponding atomic absorption coefficient.

Consider a homogeneous beam of X-rays and its absorption by a *very thin* slab of absorbing material of thickness x cm and sectional area 1 cm^2.

If n = the number of atoms per c.c., then

nx = the total number in the slab, since area of slab is 1 cm^2.

Now let N_0 = the number of photons incident normally on the face of the slab.

Bearing in mind that the intensity of a beam of X-rays is equal to the number of photons per second incident on unit area, and applying relation (6) of section 10.12, we can write

$$\text{Number of photons absorbed} = N_0 \mu x. \qquad (a)$$

If s is the atomic cross-section for the absorption process, snx = total cross-sectional area presented by all the atoms.†

* The electronic coefficient for Compton scattering $_e\sigma_a$ is independent of the nature of the scattering substance and can be calculated from an important but not simple theoretical formula, called the Klein-Nishina.

† It may be objected that all the atoms are not in one plane and consequently one atom might be directly behind another and so lessen the total cross-sectional

Since the overall area of the slab = 1 cm², it follows that, if we consider a *single* photon, the chance of its being absorbed = $\frac{snx}{1}$. Hence, when N_0 photons are incident,

the number of photons absorbed = N_0snx. (*b*)

Equating (*a*) and (*b*) we have

$$N_0snx = N_0\mu x$$

or $$sn = \mu$$

or $$s = \frac{\mu}{n}$$

= absorption coefficient per atom.

10.20. Scattered Rays and Radiography. As Fig. 10.7 shows, scattered rays may lessen the contrast of a radiograph. In this figure, *a*, *b*, and *c* represent the shadows of the objects *A*, *B*, and *C* on a film. Suppose these objects are surrounded by other particles of

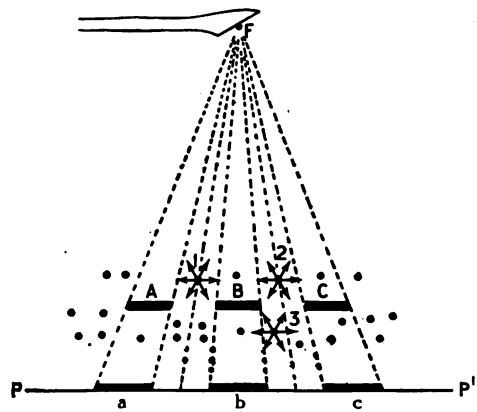


FIG. 10.7. Shadows of objects *A*, *B*, and *C* are not sharp because of scattered rays from such sources as 1, 2 and 3.

matter (as indicated by the small dots) which scatter X-rays in all directions. In that case sharp shadows would only be possible when the objects *A*, *B*, *C* were placed near the plate or film, somewhat as illustrated in Fig. 10.8. If the objects are not near the film, sharp shadows will no longer be possible, for two reasons. In the first place, the scattered rays from each particle such as 1 and 2, Fig. 10.7,

area. Because our slab is of extremely small thickness and because the dimensions of atoms are also extremely small, the probability of one covering another is so slight that we may neglect it.

will cast their own shadows, and for each particle the shadow due to this cause will occupy a different position. Again, scattered rays from many of the particles can pass under the objects and in this way affect the photographic plate in the region which the object shields from primary rays. For these reasons a good radiograph under such conditions would be impossible. Now whenever an operator wishes to make a radiograph of a thick portion of the body, he is up against this difficulty. Certain parts cannot be brought near the plate and scattering of X-rays makes it impossible to obtain good results. Can the difficulty be overcome in any way?

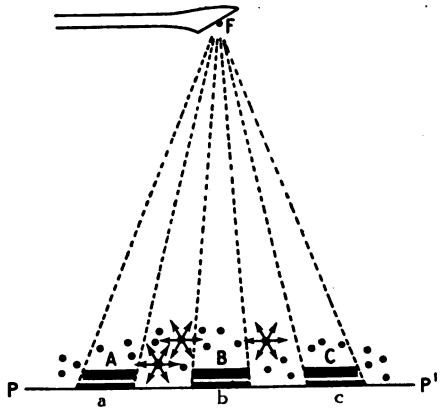


FIG. 10.8. Shadows of objects *A*, *B*, and *C* are sharp if objects are close to the photographic plate.

There are two ways in which the desired improvement in contrast may be obtained, (1) by diaphragming, (2) by the use of grids.

10.21. Diaphragms and Secondary Rays. Diaphragming consists in limiting the aperture of the primary beam by means of an opaque filter with suitable opening. In Fig. 10.9, for example, *AB* represents a diaphragm which limits the area of the beam on the plate to *MN*, whereas had a diaphragm been used of the size indicated by the dotted lines, the area would have been limited to *CD*. If now it is possible to diaphragm sufficiently when radiographing a thick body, considerable improvement in the contrast can be obtained. This may best be shown by giving some experimental results of Wilsey, of the Eastman Kodak Co., one of the pioneer workers in this field. Wilsey by a simple experimental arrangement was able to compare the photographic intensity of the primary or focal beam with

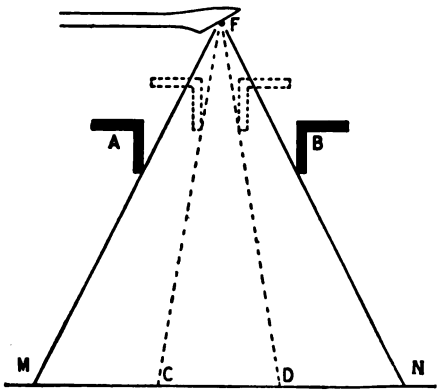


FIG. 10.9. Effect of diaphragm on the cone of rays.

that of the scattered.* Using an aperture which gave a picture on the plate 20 inches in diameter, and a layer of water 6 inches thick as the scattering material, he found the intensity of the scattered radiation to be 4·9 times that of the focal beam. By diaphragming until the picture was 8 inches in diameter scattered radiation was reduced to 4 times the focal, while if the picture were made 4 inches in diameter, the ratio was reduced to 2. In other words, if one could conveniently use a picture 4 inches in diameter, the effect of scattered rays is cut down considerably, but with a scattering layer 6 inches thick the effect of scattered rays is still twice that of the direct rays from the focal spot. While some improvement, therefore, is obtained by cutting down the aperture of the beam, the method is limited in its application and at best not very efficient.

10.22. The Potter-Bucky Diaphragm. In the Potter-Bucky diaphragm, the radiographer is supplied with an arrangement which very considerably reduces the effect of scattered rays when thick portions of the body are being photographed. The underlying principle, as first suggested by Bucky, is simple. Suppose, as shown in Fig. 10.10, a grid of lead strips, separated by narrow slots containing

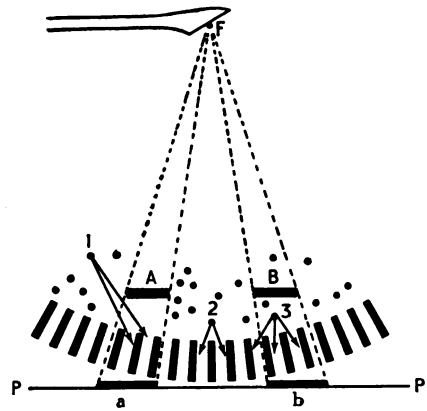


FIG. 10.10. Shadows of the objects *A* and *B* are cast only by rays travelling in the direction of the primary beam.

material of low absorption, is placed between the object to be radiographed and the photographic plate. If the lead strips are placed so that they lie lengthwise along a curve somewhat as shown in the

* Under " scattered " is also included the radiation which might be present due to rays originating at places other than the focal spot.

figure, it should be evident that if the target is so placed that the focal spot coincides with the intersection of the dotted lines in the figure, the only rays which can get through the slots and so strike the photo plate are those in the direction of the focal beam. Secondary rays in other directions are cut off by the lead strips, as is clearly shown in the figure in the case of a few rays from particles 1, 2 and 3. Sharp shadows of objects such as *A* and *B*, therefore, are cast. To avoid shadows of the lead strips showing on the radiograph, Potter suggested the use of a mechanical device for keeping the grid in motion during exposure. By this means since each portion of the plate is covered for the same length of time by each lead strip, the effect of grid shadows is eliminated. With such an arrangement excellent radiographs may be made of the thick portions of the body. The grid moves along a curved track and is thus always in the position to allow the passage of primary rays, while immediately above the grid a thin curved sheet of metal supports the patient.

10.23. Grid Ratio. In radiography this means the ratio of the depth of the opaque strips to the width of the spacing between them. (The student should note that the term grid therapy is used with a totally different meaning. See section 11.18.) In general, the higher the grid ratio, the greater the reduction of scatter. With any grid, because of the removal of scatter, exposure time is considerably lengthened. It is further lengthened because of the attenuation of the primary beam by the grid.

Exposure times can be reduced considerably by the use of higher kilovoltages (which produce a more intense beam) than have been commonly used in radiography in the past. In London at Guy's Hospital, Nemet, Cox and Hills have shown that, if suitable grids are used, medical radiographs of satisfactory contrast can be obtained with kilovoltages as high as 125 kV. In the United States work by Seeman and Splettstosser has confirmed this conclusion.

10.24. Lysholm Grid. Dr. Lysholm has shown that it is possible to use a suitably constructed *stationary* grid. In this, absorption of scattered radiation is accomplished by exactly the same means as in the Bucky diaphragm. Although it is designed for fluoroscopic use, the manufacturer of the Lysholm grid states that it may be used with advantage in radiography because the faint shadow of the lead strips " by no means interferes with the diagnostic value of the radiograph ". The grid is a light flat sheet which may conveniently be put into position and used to advantage by a radiologist whose outfit does not include a Potter-Bucky diaphragm.

PROBLEMS AND QUESTIONS

1. Describe two ways of obtaining X-rays characteristic of the matter from which they are emitted.

2. A very penetrating primary beam of X-rays traverses a layer of matter containing both heavy and light elements, and an observer with suitable apparatus examines all possible secondary emissions from the matter in a direction at right angles to the primary beam. State, with brief explanations, what he observes.

3. Explain what scattered X-rays are and discuss their importance in radiography.

4. Distinguish between scattered and characteristic fluorescent secondary X-rays.

5. Describe an experiment to demonstrate the existence of secondary X-rays.

6. Describe an experiment to enable you to find the relative intensities of the primary beam and of the secondary rays, at a given place in a medium traversed by a beam of X-rays.

7. Discuss the importance of scattered rays in radiography and show how their harmful effects may be minimized by the use of a Potter-Bucky Diaphragm.

8. Explain the construction of a Potter-Bucky Diaphragm. State why it is used and under what conditions.

9. A beam of X-rays traverses a layer of matter. Discuss what happens to the beam.

10. What is meant by the critical absorption wave length of an absorbing substance? Why is a knowledge of its value important in choosing a filter?

11. Explain why lead is not a suitable material to use as an X-ray filter under certain conditions.

12. How does the penetration in copper of X-rays of wave length 0·15A compare with those of 0·25A?

13. What is meant by (*a*) a monochromatic beam of X-rays, (*b*) characteristic X-rays, (*c*) independent or general X-rays?

14. A homogeneous radiation is reduced in intensity 50 per cent by a thickness of 0·5 mm of copper. (*a*) Plot a graph showing how the intensity falls off with increasing thickness of copper. (Note—Obtain 5 points on your graph, using copper thickness of 0·5, 1·5, 2·0, 2·5, and 3·0 mm.) (*b*) What is the name given to this type of graph? Give two examples of radiation whose absorption is governed by a graph of this kind. (*c*) Find the linear absorption coefficient for the above radiation. (*d*) If the density of copper is 8·9 gm per c.c., find the mass absorption coefficient. (*e*) Find the emergent intensity for a layer of copper 2·6 mm thick. *Ans.* (*c*) 1·38 cm^{-1}; (*d*) 0·155 cm^2 per gm; (*e*) 2·8 per cent.

15. A parallel beam of X-rays of wave length 0·080 A enters an ionization chamber, and its intensity is found to be 100. (*a*) Find the intensities when 1 mm sheets of Al, Cu, and Pb are in turn interposed in the beam. The densities are 2·70, 8·93, and 11·37 gm per c.c. respectively, and the mass absorption coefficients are 0·143, 0·263, and 2·47 cm^2 per gm respectively. *Ans.* 96·2, 79·1, 6·06. (*b*) Find the thickness of Al, Cu, and Pb which will reduce the intensity of the beam of wave length 0·080 A to half-value when interposed in turn. *Ans.* 18·0, 2·95, 0·247 mm.

16. When an unfiltered beam of X-rays is analysed by an ionization spectrometer, indicate the general nature of the curve obtained (i) when characteristic rays are absent, (ii) when they are present.

17. If the h.v.l. of a homogeneous beam of X-rays is 2 mm Al, find by how much the intensity of the beam is reduced by 6 mm Al. *Ans.* By 87·5 per cent.

18. State two practical ways by means of which K wave lengths from tungsten can be emitted.

19. Name the two classes of secondary X-rays indicating briefly what connection, if any, exists between each and (i) photoelectrons, (ii) recoil electrons.

20. Explain the meaning and the origin of (i) photoelectrons; (ii) recoil electrons.

21. When there is a change in energy due to an electron transfer in an atom, how is the wave length related to the magnitude of the energy change?

22. *Briefly* list any similarities or differences between *beta rays, photoelectrons, recoil electrons.*

23. A homogeneous beam is reduced in intensity from 100 to 80 units by 1 mm of copper. Find the intensity after the beam has passed through 4 mm of copper.

24. A photon A on striking a material gives rise to a photoelectron; a photon B to a recoil electron. In each case, explain what happens to the original photon.

25. A homogeneous beam of X-rays has a h.v.l. of 0·5 mm Cu. Find what per cent is transmitted by 1·4 mm Cu. *Ans.* 14·4 per cent.

26. Using the data in question 25, find the linear absorption coefficient.

27. (*a*) If it requires 25·6 keV to excite all the K wave lengths of a certain element and the wave length of $K\alpha$ radiation is 0·561A, estimate how much energy is necessary to remove an electron from the L shell. *Ans.* 3·5 keV.

(*b*) If electrons possessing 18 keV bombard a target made of this element, find the kinetic energy of a liberated L electron.

28. You are given that $\frac{\tau}{\rho}$ for tungsten ($Z=74$), for wave length 0·179A, is 16 cm^2 per gram. Estimate the value of $\frac{\tau}{\rho}$ for rubidium ($Z=37$), for wave length 0·09A. (See section 10.16.)

29. Calculate the h.v.l. in aluminium and in copper for X-rays of a certain wave length, given that for this wave length $\frac{\mu}{\rho}$ for Al is 5 cm^2 per gram and for Cu 50 cm^2 per gram. Density of Al = 2·7 gm per c.c.; of Cu = 8·9 gm per c.c.

30. Given that for an unfiltered beam of X-rays the effective absorption coefficient is 6·9 cm^{-1} in aluminium, find the reduction in dosage delivered to a patient's skin when a filter of Al 1 mm thick is used.

31. If 1 mm of a material absorbs 30 per cent of a homogeneous beam of X-rays, find the thickness required to absorb 80 per cent. *Ans.* 4·5 mm.

32. A metal plate of thickness 2 mm absorbs 40 per cent of a certain beam of X-rays. Calculate the effective absorption coefficient.

33. If 3 mm Al absorbs 40 per cent of a homogenous beam of X-rays, find the h.v.l. in Al for this beam. *Ans.* 4·07 mm.

34. You are given that 69·3 keV are necessary to excite all the K wave lengths of tungsten and 10·4 keV the L wave lengths. Estimate the mean wave length of the $K\alpha$ radiation. *Ans.* 0·21A.

CHAPTER XI

MEASUREMENT OF DOSAGE FOR ROENTGEN RAYS

11.1. Quality and Intensity. In the field of radiology, X-rays are used in two general ways: (1) in diagnosis, either by photography or by the use of the fluorescent screen; and (2) in therapy, where the aim is to bring about a beneficial effect on diseased tissue. In the latter field, where the rays are an agent for treatment, it is just as important to know the "dose" as it is in prescribing ordinary medicines. In either case, too large a quantity may kill instead of cure the patient. It is necessary, therefore, to consider somewhat in detail this whole question of dosage.

First of all, it will be evident that to describe accurately a given beam of X-rays two things must be known: (1) its quality; and (2) its intensity at any particular place in the path of the beam. We have already explained how the quality is described by giving the constituent wave lengths of the beam, or its effective wave length, or the h.v.l. in some standard material. So far, however, although some use has been made of the idea of intensity, the exact meaning of this term and its relation to dosage has not yet been discussed. This is done in the following pages.

11.2. Intensity and Law of Inverse Square. From the focal spot on the face of the target of an X-ray tube, a beam of X-rays spreads out in much the same way as ordinary light rays from a small source of light. In each case energy is radiated from the source, and in each case the intensity of the beam at any point is measured fundamentally by the radiant energy which each second passes through unit area placed at right angles to the direction of the beam at this point. The unit of intensity is then 1 erg per cm^2 per sec, or, if a larger unit is desired, 1 watt* per cm^2. Quantity of radiation, which is the product of intensity $\times$ time, is measured in ergs per cm^2.

In either case, if no energy is lost by absorption, it is not difficult to see that the intensity falls off with increasing distance according to the inverse square law. In Fig. 11.1, all the energy which passes through the area *ABCD* also passes through the area *A'B'C'D'*, since

* 1 watt $= 10^7$ ergs per second.

both X-rays and light rays are propagated in straight lines. Now if the distance FA' is exactly twice FA, then the *area* $A'B'C'D'$ is exactly four times the area $ABCD$. Therefore the energy received

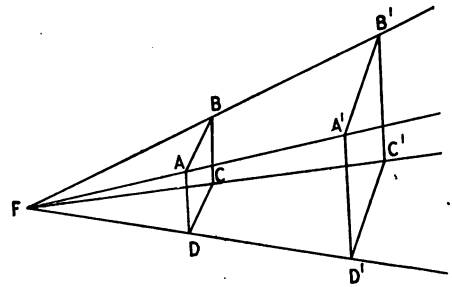


FIG. 11.1. If $FA' = 2FA$, then the area $A'B'C'D' = 4$ area $ABCD$.

per second per unit area at any point in $A'B'C'D'$ is one quarter of the energy received per second per unit area at any point in $ABCD$. In other words, if we double the distance, the intensity falls to one quarter the value, or, in general, the intensity falls off inversely as the square of the distance from a small source, provided there is no absorption.

11.3. X-ray Dosage. General Ideas. When X-rays are used for treatment, part of the energy of the beam is absorbed, part is transmitted. Since the transmitted portion can play no part in any beneficial or harmful effects the rays may have on tissue, the radiologist is interested primarily in the absorbed portion. The student, therefore, should distinguish clearly between the intensity or energy flux rate of X-rays and the *dose-rate*, that is, the rate at which energy is absorbed by a medium like tissue. In dosage we are concerned with the energy dissipated in the medium.

Since it is not possible to measure directly the amount of energy absorbed in tissue, in the early days of X-ray therapy attempts were made to establish units of dosage by making use of various effects arising from the absorption in other media. For example, use was made of a unit based on a change in colour of certain salts, in the form of pastilles, brought about by the absorption of a definite amount of X-ray energy. Gradually, however, it became evident that the ability to ionize air was the only property* of X-rays which could be used conveniently for obtaining a suitable physical unit having a direct relation to tissue dosage. There are several reasons for this.

* As will be seen later, the degree of blackening of a photographic film is also used in special circumstances.

(1) Over a wide range of wave lengths the ionization of air is directly proportional to the X-ray energy absorbed.

(2) Since tissue is largely composed of the light elements hydrogen, oxygen, carbon and nitrogen, what we might call the effective atomic weights of air and of tissue do not differ to any great extent. It is useful to remember that, over a wide range of wave lengths, *the absorption per gram is nearly the same for air, for water, and for tissue.*

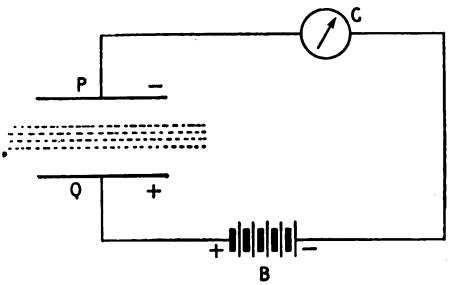


FIG. 11.2. A very sensitive galvanometer G indicates a current when a beam of X-rays ionizes the air between P and Q.

(3) Closely related to (2) is the fact that the absorption of air changes with changing wave length in the same way as the absorption by tissue.

(4) It is highly probable that the primary cause either of the beneficial or of the injurious effect of X-rays on tissue is due to ionization. (At the same time, we add here a note of warning, because equal amounts of ionization produced in tissue by different types of ionizing particles do not always give rise to the same biological effect. See Appendix A.)

(5) The ionization method of measuring absorbed X-ray energy lends itself to the establishment of a convenient, universal unit, which may readily be realized.

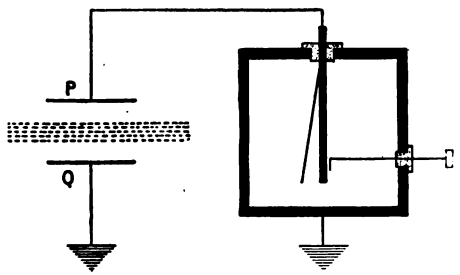


FIG. 11.3. A charged electroscope attached to P is discharged when a beam of X-rays ionizes the air between P and Q.

It is necessary, therefore, to study in detail the whole question of ionization of air and its use in the measurement of X-ray dosage.

11.4. Saturation Ionization Current. Consider the two arrangements illustrated in Fig. 11.2 and in Fig. 11.3. In Fig. 11.2, two plates, P and Q, separated by an air gap, are joined in series with a battery B and a very sensitive galvanometer. In Fig. 11.3, the plate Q is grounded and the insulated plate P is joined to the leaf of an electroscope. With the galvanometer arrangement there is normally

no current because for moderate voltages air is a good insulator. With the electroscope arrangement, if the insulated plate and the leaf are given a charge, the leaf remains stationary for the same reason.* Now suppose a beam of X-rays, indicated by the dotted lines in these figures, traverses part of the region between the plates P and Q. The air in its path is then ionized and, in the arrangement of Fig. 11.2, the galvanometer (if sensitive enough) indicates a current or, in Fig. 11.3, the leaf of the electroscope falls. A steady deflection is recorded by the galvanometer, because as long as the X-ray beam is in action, there is a steady stream of ions, positive to the negative plate, negative to the positive. If the insulated system in the electroscope

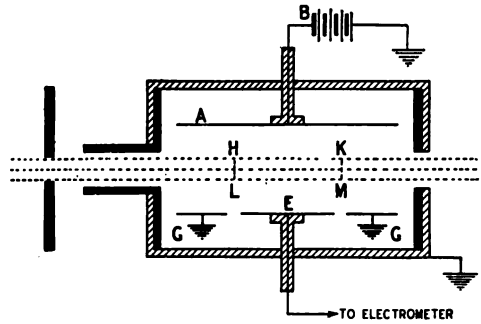


FIG. 11.4. The essential features of a standard ionization chamber.

arrangement is positively charged, negative ions will go to P (positive to the earthed plate Q), and the leaf will drop at a rate which depends on the magnitude of the current of ions.

Should the beam of X-rays be made more intense, a greater number of ions is formed in each unit volume, a bigger ionic current flows, and a greater deflection is recorded by the galvanometer; or, with the other arrangement, the leaf falls at a faster rate. Hence, either arrangement provides us with a convenient means of measuring the (absorbed) intensity of an X-ray beam, the first by the steady deflection of a galvanometer, the second by the rate of fall of the leaf of an electroscope. To make sure that the galvanometer deflection or the rate of fall of the leaf is *exactly* proportional to the absorbed intensity, an important condition must be fulfilled, and that is, the ionization current must have its saturation value. This means that

* Actually, due to defective insulation and to a *very slight* amount of ionization present at all times in the air, the leaf falls very slowly, so slowly that often it can be neglected. In making exact observations it is an easy matter to correct for this *natural leak* as it is called.

the potential difference between the plates P and Q must be large enough to remove all the ions as fast as they are formed. If the voltage is too small, some of the positive ions will unite with negative, or, to use the technical term, a certain number of positive and negative ions will *recombine*. The voltage, therefore, must be sufficiently high to prevent *recombination* so that as many ions reach the plates per second as are manufactured by the ionizing beam.

In any of the arrangements we shall later describe, it is assumed that sufficient voltage is used to ensure saturation.

11.5. Ionization Chambers. In the arrangements used practically to measure ionization currents, the plates P and Q of Fig. 11.2 and Fig. 11.3 correspond to what is called an *ionization chamber*. We

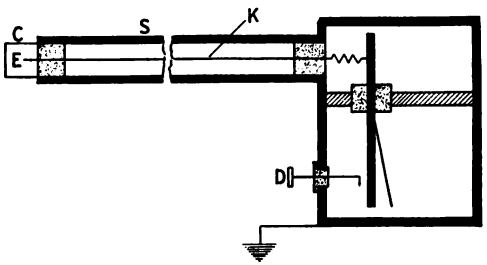


FIG. 11.5. Arrangement for using a small ionization chamber C and an electroscope.

distinguish two main kinds: (1) the *standard*; and (2) the small *thimble* chamber. The essential features of a standard chamber are shown in Fig. 11.4. In this arrangement ions resulting from the absorption of the beam of X-rays in the volume *HKLM* are driven to the collecting electrode E because of the electric field maintained between the plates A and E by the battery B, and the total charge coming to the electrode in any given time is measured by the instrument attached to E. Further details about the use of the standard chamber will be given presently. At this stage it is sufficient to state that it is not suitable for use by a practising radiologist, but is used for standardization purposes.

The essential features of a simple arrangement with a thimble chamber are illustrated in Fig. 11.5. C represents the chamber, which encloses a volume which may be of the order of one or two cubic centimetres. Its walls are of some light material—even paper will do—whose inner surface is made conducting by a thin coating of graphite and is grounded. E, the insulated electrode to which ions

are attracted is joined to a measuring instrument, such as an electroscope or other type of electrometer, by the insulated conductor K. This conductor is shielded from electric disturbances by surrounding it with an outer earthed tube or shield S. To prevent ionization in the region between K and the outer tube, this space may be filled with an insulating material like rubber, or, by means of a vacuum pump, the pressure in this region may be kept so low that ionization by any radiation penetrating the shield may be neglected. If desired the tube connecting the electrode to the electrometer may be flexible and of any convenient length. A description of a chamber in common use is given in section 11.12.

11.6. The Roentgen. Before discussing further details concerning ionization chambers, it is desirable at this stage to explain the nature of a unit of a specific quantity of X- and gamma radiation which is defined in terms of energy absorption in air and for many years has been used also as a unit of dosage. Its relation to the true dose, that is, the energy absorbed per gram of tissue, is explained in section 11.20.

Whatever arrangement is used to measure the ionization current resulting from X-ray absorption in air, it should be evident that its magnitude depends on two factors, (1) the intensity of the beam, and (2) the volume of air from which the ions are removed. The greater the intensity, the greater the number of ions manufactured in each cubic centimeter; and, for a given intensity, the larger the volume from which the ions are collected, the greater the total number taking part in the current to the collecting electrode.

With these facts in mind, the student should be able to understand, at least in a general way, why in 1928 the Second International Congress of Radiology adopted the following definition of a physical unit, called the *roentgen*.

The *roentgen is the quantity of X-radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in* 1 *c.c. of atmospheric air at* 0° *C. and* 760 *mm pressure, such a degree of conductivity that one electrostatic unit of charge is measured at saturation current.*

In 1937, at the Fifth International Congress, this definition was altered to the form given in section 11.7. (In 1950 and in 1953, the 1937 definition was confirmed.) Since for X-rays generated by means of voltages as high as about 200,000, the two definitions agree in their practical application, we shall make use of the 1928 definition in our initial discussion.

It will be recalled that the electrostatic unit of charge (e.s.u.), which we have previously designated the statcoulomb (section 3.5), is such a quantity that when it is placed 1 centimetre away, in air, from an equal quantity, the force of repulsion of one on the other is 1 dyne. In actual calculations, it is more convenient to know that the coulomb, the practical unit of quantity, is related to the statcoulomb by the equation,

$$1 \text{ coulomb} = 3 \times 10^9 \text{ statcoulombs.}$$

Suppose, in an arrangement like Fig. 11.4, a current of 10^{-9} ampere is recorded by the measuring device and that the volume *HKLM* in which the ions are produced is 10 c.c.

Since 10^{-9} ampere $= 10^{-9}$ coulomb per second,

$$= 10^{-9} \times 3 \times 10^9 \text{ statcoulombs per second,}$$

$$= 3 \text{ statcoulombs per second,}$$

we may write: The number of statcoulombs produced in 10 c.c. in 1 sec. = 3. Hence, the number produced per c.c. in 1 sec. = 0·3. According to the above definition, the dose-rate of the beam producing the ions in the region *HKLM*, is 0·3*r* units per second. This assumes that the air is at 0° C. and 76 cm pressure. For other temperatures and pressures, we apply the elementary gas laws and write

V c.c. at $t°$ C. and P mm pressure

$$= V \times \frac{273}{273+t} \times \frac{P}{760} \text{ c.c. at } 0° \text{ C., and } 760 \text{ mm.}$$

In any problems given in this text, we shall assume that this volume correction has been made.

If the above beam continued in operation for 10 minutes, the dose delivered in the region *HKLM* would be $0{\cdot}3 \times 10 \times 60$ or $180r$ units.

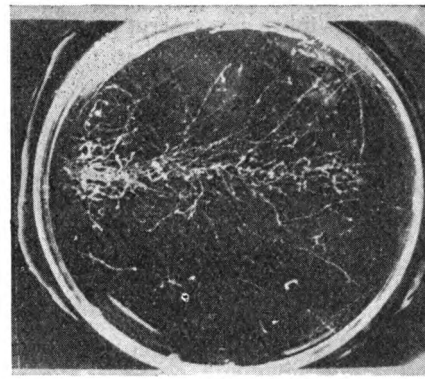
To fulfil the conditions expressed in the above definition of the roentgen certain precautions must be taken.

(1) The current must have saturation value; (2) all the secondary electrons must be utilized; and (3) the wall effect of the chamber must be avoided. Let us examine each of these in turn.

(1) The meaning of saturation has already been explained and need not be further discussed.

(2) We have also previously explained that when a beam traverses a gas like air the ionization is due to the action of photoelectric and recoil electrons. Now these liberated electrons may travel outside the track of the primary beam, as shown by the cloud track photo-

graph in Fig. 10.2. For long wave lengths the " outside " effect is slight, but if the wave length of the primary beam is made shorter and shorter, the excursion of the electrons out of the track becomes



Courtesy Charles C. Lauritsen

FIG. 11.6. Passage of 550,000 volt X-rays through a cloud chamber. Note the long excursion of the electrons.

longer and longer. This means that *ionization often takes place well outside the actual region traversed by the primary beam.* This long excursion of the electrons is nicely shown in Fig. 11.6, a reproduction of a photograph taken, with tube voltage 550 kV, by Dr. Walter Jordan at the California Institute of Technology and reproduced through the kindness of Dr. Charles C. Lauritsen. The tube voltage used when Fig. 10.2 was taken is not available, but it is very much less than 550 kV. If then all the ions are to be utilized—" the secondary electrons fully utilized "—*the separation of the electrodes must be sufficient to insure that none of the electrons strike containing walls before they have used up their energy in ionizing.* The actual separation depends on the kind of rays used, being greater the shorter the wave length. For X-rays generated by voltages up to 180,000 or 200,000 volts, a spacing of 12 cm is sufficient, but for X-rays generated by a million volts, the range of secondary electrons is so much greater that the overall dimensions of the standard chamber must be greatly increased. For X-ray energies exceeding 2 or 3 MeV, measurements in roentgens are impracticable and the roentgen should not be used. For these high energies the conditions for electron equilibrium explained in section 11.9 cannot be satisfied.

In this connection the student may well ask : " If ions are formed outside the region *HKLM* (Fig. 11.4), is it correct to use only the

volume of *HKLM* in making calculations?" In considering the answer to that question the student must distinguish carefully between: (*a*) the *conversion process*, whereby part of the energy of an X-ray beam is truly absorbed, being converted into the kinetic energy of photoelectrons and/or recoil electrons, and (*b*) the subsequent process in which these secondary electrons gradually lose their energy by creating ions along their paths. Obviously, in a standard chamber, the ions are drawn to *E* from the *whole region* between the electrodes of width equal to *HK* or *LM*, although the conversion process takes place in the region *HKLM*. For X-rays of very short wave length many of the ions formed by the ejected electrons are outside this region. (See Fig. 11.6.) Although the 1928 definition of the roentgen does not state the fact explicitly, the cubic centimetre in that definition does refer to the region *HKLM* where the electrons are liberated by the primary beam, that is, where the energy conversion process takes place. In this respect the 1937 definition discussed in the next section is more exact.

(3) If X-rays are allowed to strike the walls of the chamber, secondary X-rays and electrons may be emitted, and these may add to the ionization of the air between the electrodes. In an actual standard chamber, therefore, the primary beam is carefully isolated by protecting diaphragms, with the electrodes well separated as noted above. As a still further precaution, the walls of the chamber are made of materials of low atomic weight so that if any stray radiation did strike them, the emitted fluorescent rays would be so soft (see section 8.7) that they would be absorbed before having produced any appreciable ionization.

Since the accuracy of all measurements in roentgens depends ultimately on the standard free air chamber, it is highly important that it should be capable of the utmost precision and, moreover, that a high order of agreement should exist between the primary standards of different countries. In spite of previous work spread over many years, Kemp in 1953 and Kemp and Hall in 1954 showed that there were slight errors in the primary standards of both Britain and the U.S. Recent joint work between the N.P.L. at Teddington and the N.B.S. at Washington has revealed also the existence of small errors when a new primary standard at the N.B.S. was compared with both the previous one at that institution and the N.P.L. instrument. A new chamber has been constructed at the N.P.L. and (in 1955) this is to be sent to the United States for direct comparison with the N.B.S. standard.

11.7. 1937, 1950, and 1953 Definition of the Roentgen. At the Fifth International Congress of Radiology held at Chicago in 1937, a somewhat different definition of the roentgen was adopted. Although the altered definition was made applicable to the highly penetrating gamma rays, it should be noted that in 1953 when no change was made in the definition, the proviso was added that it " may be used for practical purposes up to 3 MeV ". The new definition reads as follows :

The roentgen shall be the quantity of X- or gamma radiation such that the associated corpuscular emission per 0·001293 *gram of air produces, in air, ions carrying* 1 *e.s.u. of quantity of electricity of either sign.*

In many respects the two definitions are identical, and no change need be made in the work of the preceding pages. Note, however, the following :

(1) 0·001293 grams is the mass of 1 c.c. of air at 0° C. and 760 mm pressure.

(2) Saturation conditions are not mentioned because the definition refers to the number of ions *produced* per cubic centimetre by the radiation and naturally includes all of them. In making measurements, however, it is just as necessary as ever to use sufficient voltage to ensure that the ions do not recombine.

(3) The ions to be considered are those produced by the corpuscular emission per 0·001293 grams, that is, by the secondary electrons (photoelectric and recoil) set in motion by the primary beam. This corresponds to the clause in the 1928 definition requiring the utilization of all the secondary electrons, but, as already noted, specifies without any ambiguity that the volume to be used in calculating the number of r units is the volume of the region in which the primary beam produces its " associated corpuscular emission ".

11.8. Determination of Effective Volume. In considering the exact value of the volume *HKLM* to be used in calculating the number of r units, two factors are of importance. The first has to do with the nature of the electric field between the charged plate A, Fig. 11.4 and the collecting electrode E. Since charged particles move along electric lines of force, the ions in an arrangement like that shown in Fig. 11.7*a*, move to E out of the region *MNCD*. The volume of this region varies with the relative size of the plates and is not easy to measure. For accurate calculation, the lines of force should run as nearly perpendicular as possible over the whole face of the electrode E, somewhat as shown in Fig. 11.7. This is accomplished by surrounding this electrode with the grounded guard

plates G and G. If initially E is also grounded, as is usually done in standard measurements (see section 11.10), and if the gap between E and the plates GG is narrow, then the ions are drawn to E from the region between the electrodes whose length is equal to the distance from the centre of the narrow opening on one side of the

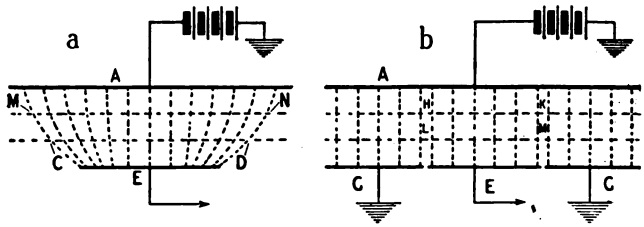


FIG. 11.7. By the use of guard plates G and G a uniform electric field can be maintained between A and E, as in b. In a the field is far from uniform.

electrode to the centre of the other opening, that is the length HK or LM.

The second factor refers to the cross-sectional area of the beam of X-rays which is limited by the diaphragm S, Fig. 11.4. In this figure, and in Fig. 11.7 (b) the area represented by HL is shown as equal to the area MK, but in an actual arrangement, the beam is slightly divergent as shown in Fig. 11.8, and hence in this figure the

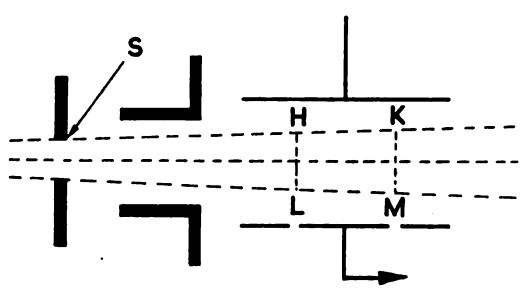


FIG. 11.8. In a standard ionization chamber, although the beam is slightly divergent, the correct dose *at S* is obtained by using the product, area of diaphragm at S × length LM or HK, as the volume in which ions are produced.

area KM is slightly greater than the area HL. Instead of estimating the divergence and then calculating the dose in roentgens at the centre of the volume $KHLM$, more frequently the dose *at S* is calculated using the volume obtained by multiplying the area of *the*

opening at S by the length *HK* or *LM*. It follows from the inverse square law that, as far as the production of ions is concerned, this volume is the exact equivalent of the volume *HKLM* when calculated using the correct areas *HL* and *KM*.

11.9. Electronic Equilibrium. By examining Fig. 11.9 the student should be able to understand readily several things : (1) ions will go to the electrode *CD from the whole region ABCD* ; (2) electrons which originate in the region *HKLM*, but most of whose ionizing paths (such as 1 and 2) are outside the volume *ABCD*, will create many ions which do not go to the collecting electrode ; and (3) other electrons (such as 3 and 4), which did not originate in the region *HKLM*, will create ions within the volume *ABCD* which do go to the

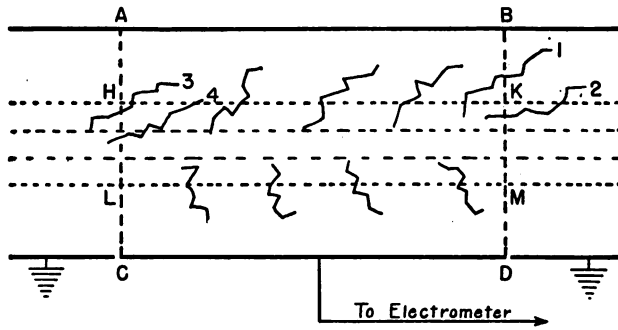


FIG. 11.9. Lines 1 and 2 represent tracks of electrons produced in the region *HKLM*, lines 3 and 4, tracks of electrons produced outside this region.

electrode. There is therefore a loss of ionization from electrons which have moved out of *ABCD* and a gain from other electrons which have moved into this region. In standard ionization chambers designed for highly penetrating rays which give rise to secondary electrons with long paths, the loss can be made equal to the gain by making sure that the dimensions of the chamber are sufficiently large that electrons move into the volume *ABCD* from distances equal to the maximum forward range of those which move out.

When this condition is fulfilled we have what is called *electronic equilibrium*. Stated otherwise, this means that for each electron leaving the region from which ions are collected, an electron of equal energy must enter it. Since for 5 MV X-rays the range of electrons in air is 20 metres and for 50 MV is 170 metres, it should not be difficult to see that conditions for electronic equilibrium cannot be satisfied with radiations of extremely high energies.

11.10. Null Method of Measuring Ionization Current. It has been stated in the preceding section that a suitable electric field is obtained in a standard chamber when both the guard plates *GG*, Fig. 11.7*b*, and the electrode *E*, are at ground potential. In actual use *E* is initially grounded, but this connection to earth must be broken before any measurement can be made of the charge carried to *E* by the ions, in any time interval. If this charge were measured by direct connection to an electrometer, the potential would steadily change as time went on, and in consequence the electric field would also change sufficiently to introduce an appreciable error in the calculated volume. To overcome such an error, in laboratories such as the Bureau of Standards in Washington, and the National Physical Laboratory, Teddington, a null method is used. Fig. 11.10 illustrates in simple form the arrangement used in one such method. *E*, it will be seen, is connected both to the measuring electrometer and to one side of a standard condenser *C* whose capacity is accurately known. The other side of the condenser is connected to a source of potential whose magnitude may be varied, the polarity being so chosen that the charge on the side of the condenser connected with *E* is opposite in sign to the charge on the ions coming up to *E*. When a measurement is being made, initially the key *K* is closed, thus grounding *E* and the system to which it is attached. With the X-ray beam in operation, *K* is then opened, and a stream of ions begins to flow to *E*. But, as *E* accumulates a charge, the potential applied to the condenser is steadily altered in such a way that an equal charge of opposite sign is induced on the side of the condenser connected with *E*. The *resultant* charge on the system joined to the electrometer is therefore kept at zero, and the indicator of the electrometer remains unchanged in position.

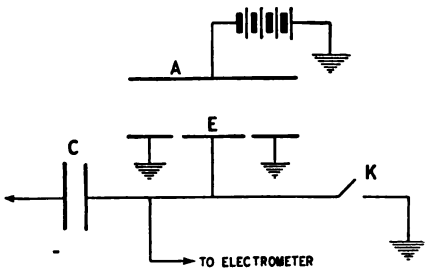


FIG. 11.10. By varying the voltage across the condenser *C* the ionic charge coming to *E* may be annulled, thus keeping *E* at the original ground potential.

To determine the total charge *Q* coming to the electrode in an observed time *t*, all that is necessary is to calculate the magnitude of the charge given to the condenser. A numerical example will illustrate the method.

The dose-rate of a beam of X-rays at a certain place was measured by a

standard ionization chamber arranged so that the effective volume in which ions were produced was 2·51 *c.c. When the collecting electrode was attached to a condenser of capacity* 127×10^{-6} *microfarad, it was found that the electrometer remained undeflected if at the end of* 1 *minute the potential applied to the condenser was changed by* 9·2 *volts. Calculate the dose-rate in r units per minute.* (The volume refers to air at 0° C. and 760 mm pressure.)

Q = compensating quantity on condenser
= capacity × potential
= $127 \times 10^{-6} \times 10^{-6} \times 9{\cdot}2$ coulombs*
= $127 \times 10^{-12} \times 9{\cdot}2 \times 3 \times 10^{9}$ statcoulombs
= 3·505 statcoulombs.

Therefore, the number of statcoulombs collected in 1 minute, if the volume were 1 c.c.

$$= \frac{3{\cdot}505}{2{\cdot}51} = 1{\cdot}4,$$

or, the dose-rate of the beam

$= 1{\cdot}4r$ units per minute.

11.11. Thimble Chambers. Because of its fundamental importance, detailed attention has been given to the explanation of the means of measuring in r units per second the dose-rate of a beam of X-rays by the standard chamber. In actual practice, the radiologist or his technician makes use of the thimble type of chamber rather than a standard because by such means in a very short time he can evaluate the dose in r units or the dose-rate in r units per second. It should never be forgotten, however, that previously someone had to calibrate his thimble chamber with the aid of a standard.

We must now amplify the information about small ionization chambers given in section 11.5. To begin with, it is well to note that, except in rare cases, the ionization produced per cubic centimetre in a small chamber is not the same as that produced per cubic centimetre by the same beam at the same place, in free air. There are several reasons for this. (1) Because of absorption of the primary beam by the walls of the chamber, the ionization is reduced. This effect can be lessened by using chamber walls of extreme thinness, but (2) whatever the thickness, secondary electrons emitted by the wall material increase the ionization. (3) The corpuscular electrons produced

* 1 microfarad = 10^{-6} farad. An alternate method of calculating the number of coulombs is to use the relations 300 volts = 1 statvolt and 1 microfarad = 900,000 statfarads.

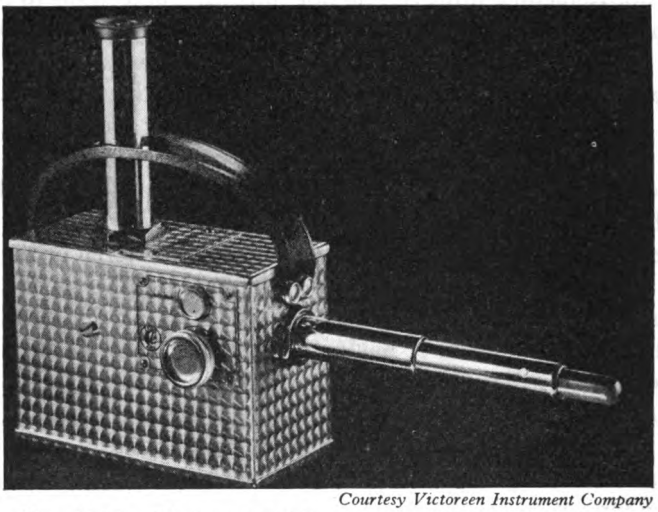
within a small volume strike the walls before they have exhausted their ability to ionize.

The above factors, however, do not constitute objections to the use of thimble chambers, because as already noted, they are calibrated by means of a standard chamber. What is of great importance, is the requirement that the ionization as measured by the small chamber should be directly proportional to that measured by the standard, *over a wide range of wave lengths*. When this condition is fulfilled, the chamber is said to be of the " air-wall " type as distinguished from the " free-air " standard chamber. Practically this result can be obtained by making the walls of the chamber of material or materials of low atomic weight, so that the mean atomic number is about the same as air ($Z=7{\cdot}4$). For example, to quote L. S. Taylor, " it is thus possible to make a chamber having a graphite shell with aluminium collector which will give readings nearly proportional to the open-air chamber over a wide wave length range of the harder radiations." Again, we quote from the 1937 Recommendations of the British X-ray and Radium Units Committee " . . . it is an experimental fact that the ionization in chambers suitably constructed and lined with certain mixtures, though not necessarily equal to the ionizations produced by the same beam of radiation in air, is proportional to it over a wide range of wave lengths ". An air equivalent chamber has been made of a material consisting of 80 per cent bakelite, 19·8 per cent carbon and 0·2 per cent vanadium pentoxide.

Strictly speaking, an air-wall chamber is one whose walls are so chosen as to material and thickness that the dosage in roentgens recorded by the use of the chamber is the same as in free air ; that is, that the ionization produced per cubic centimetre in the chamber is the same as in free air. In actual practice a standard chamber of this kind is not necessary because commercial chambers such as the one descibed in the next section are calibrated against standard free air chambers before they are put in the hands of radiologists.

11.12. Victoreen Condenser-Meter. This type of instrument, a photograph of which is reproduced in Fig. 11.11, consists of two main parts : (1) a narrow cylindrical piece, E to B, Fig. 11.12, which at one end has an ionization chamber C ; and (2) a box housing a fibre electrometer (electroscope), a device for giving an electric charge to the electrometer, and a lamp L to illuminate the fibre. On top of the box a low power microscope $\mathcal{J}$ to I enables an observer to view the image of the fibre against a scale. The central electrode of the ionization chamber passes through solid insulating material such as amber,

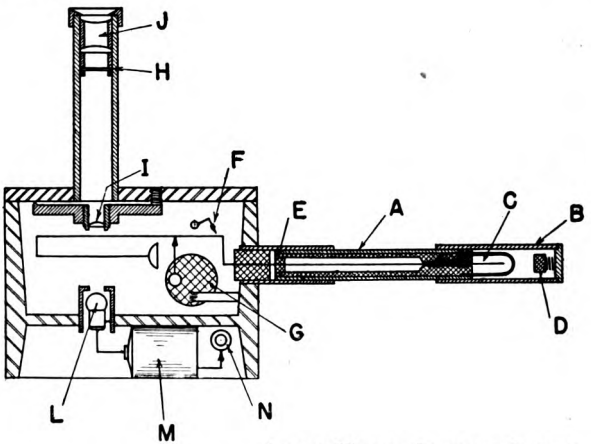
and on emergence at the end E of the cylinder next the box makes electric contact with the fibre of the electrometer. It will be noted



Courtesy Victoreen Instrument Company

FIG. 11.11. Photograph of the Victoreen Condenser r-Meter.

that the main body of the cylinder is essentially a condenser, consisting of the central conductor, the dielectric surrounding it, and the outer earthed wall.



Courtesy Victoreen Instrument Company

FIG. 11.12. Diagram showing details of the Victoreen Condenser r-Meter.

In use, the insulated system, fibre plus connecting conductor and central electrode, is given such a charge that the image of the fibre,

which is deflected an amount proportional to the potential to which it is charged, comes to rest on the zero of the scale. The cylindrical tube, which is attached to the box by a kind of bayonet socket, is then detached, and the cap *B* protecting the ionization chamber is removed and placed over the opposite end *E* of the tube thus protecting the exposed end of the central conductor. The tube is then held with the ionization chamber in the path of the X-ray beam at the place where the dose-rate is to be measured, for a measured time interval, which is frequently 1 minute. Because of the resulting ionization in the chamber a *part* of the charge on the collecting electrode and attached condenser unit is neutralized. At the end of the minute the cylinder is taken out of the X-ray beam, the protecting cap replaced over the chamber, and the tube inserted into the box so that electrical connection is once more made with the electrometer. Because of the loss of charge, the potential of the electrometer drops a certain amount and the fibre, or its image, moves from the original zero to another part of the scale. Because of previous calibration the numbers on the scale read roentgens directly. Thus, if 15 were now read on the scale, the dose-rate of the beam at the spot where the chamber had been placed, would be 15*r* units per minute.

By using different types of tubes and chambers condenser meters of various ranges are available. For example, the Victoreen Instrument Company advertise meters reading up to 25*r*, 100*r*, and 250*r* units per minute, as well as a very sensitive one for measuring stray radiation reading only to 0·25*r* per minute. This firm states that with a single chamber, " measurement is possible for any wave length radiation from that produced by a standard X-ray tube at 60 kVp up to and including gamma rays of radium, with a wave length error not exceeding 6 per cent at both extremes. A calibration curve can be supplied giving the necessary correction, if any, within 2 per cent."

Dosimeters involving more or less the same fundamental principles are available, which record the *total* dose in *r* units during the progress of a treatment. In the Victoreen Integron, for example, the progress of a dose up to 300*r* units may be watched by means of a pointer moving over an ordinary scale. In the Hammer Dosimeter, the electrical arrangement is such that every time a collecting electrode has acquired a charge equivalent to a dose of 5*r* units, a clock mechanism moves the hand of a dial one division, while at the same time the electrode is discharged and made ready to collect another charge.

11.13. Chamber Walls. For X-rays in the region in which the secondary electrons are chiefly recoil, the composition of an air-wall

chamber is not highly critical, because the intensity of these electrons is almost independent of the material, for all light elements with the exception of hydrogen.

For very soft radiation, however, the composition of the walls is highly critical. For these rays the secondary electrons are almost entirely photoelectric and their intensity, it will be recalled, is a marked function of both the wave length and the atomic number.

But whatever the wave length used, the thickness of the walls of a chamber is of the utmost importance if electronic equilibrium is to be attained. Except for Grenz rays, the ionization in the chamber is due primarily to the electrons liberated in the wall and only slightly to those liberated in the air enclosed in the chamber. Since both the range of electrons in the wall and the absorption of the primary beam by the wall depend on wave length, wall thickness must be carefully chosen. For X-rays generated by say 100 kV to 200 kV the range of electrons is a fraction of a millimetre and a wall of that thickness is required. For more penetrating rays, where the range of the electrons exceeds 1 mm, a corresponding wall thickness is used. For rays with quantum energies of a few MeV, the required thickness is about 4 mm. Mayneord has made measurements with 30 MeV X-rays, " in which case the air cavity must be surrounded by some 5 centimetres of light element material to give the necessary equilibrium." (Spiers.)

When extremely soft Grenz rays are used, and with the use of low voltage tubes and beryllium windows these have become of increasing importance, the design of a suitable chamber becomes more important. Attenuation due to wall absorption now becomes of great importance. Measurements made some years ago by Victoreen, Atlee and Trout in the United States emphasize the difficulties encountered with low voltage rays. They reported that for a wave length of 1·3 A, a Victoreen chamber recorded 40 per cent less than the standard and for a wave length of 1·4 A, 50 per cent less.

The difficulties can be met to a considerable extent in more than one way. In one type of instrument, a *mesh chamber*, the rays enter through a fine mesh. Somervil of Holland, for example, describes a mesh chamber in which there is negligible absorption because both the collecting electrode and the electrically charged walls defining the region from which ions are collected are made of a grid of carbon-coated nylon threads, 50μ in diameter, 1 mm apart.* The distance

* In addition, there are two outer grounded mesh walls, whose purpose is to prevent ions entering into the collecting region from outside it.

between the collecting electrode and a wall is of the order of 2 mm, but the walls are movable. The chamber, therefore, is of the extrapolation type, whose principle is described in section 11.15.

A different type of low voltage chamber, with rigid walls, has been described by Oosterkamp of Philips (Holland). In this instrument, made chiefly of graphited polystyrene, the rays enter the ionization region, a thin cylindrical layer of volume 0·02 c.c., through a window whose thickness is small but not negligible, being 0·2 mm in one chamber, 0·45 mm in another. By making the effective atomic number *less* than that of air and by suitably choosing the dimensions of the chamber, compensation is made for the change in attenuation with changing wave length and also for the changing proportion of ionization due to secondary electrons in the wall as compared with electrons liberated in the air itself. Oosterkamp states that with chambers of this type, wave length independence is obtained over a considerable range, extending in one instrument from an h.v.l. in Al of 0·02 to 1 mm, in another from 0·04 to 2·5 mm.

11.14. Dose-Rate Meters. Although the Victoreen Condenser-meter in its standard use is a dose-rate meter, and in the Integron is an integrating dosimeter, it is sometimes desirable to have direct reading meters for both purposes. A brief reference only is made to the principles involved in these instruments. In the dose-rate meter the current in the ionization chamber is amplified by electronic methods. The amplified current, which is proportional to the chamber current and so to the dose-rate, is read directly on an instrument like a microammeter, whose scale can be calibrated to read directly in *r* per minute.

In the integrating dosimeter, a condenser is so placed in the input circuit, that as the chamber current continues, the potential to which the condenser is charged steadily rises. Since the value of this potential is a measure of the *integrated* current and so of the dose, the output current from an amplifier which increases as the potential rises, is at any instant a measure of the dose received by the chamber up to that instant.

Before explaining the relation of the roentgen to the rad, the energy unit of dosage, it is desirable to give some additional general information about dosage.

11.15. Air Dose, Tissue Dose and Back Scatter. In therapy the radiologist is interested primarily in the dose delivered to *tissue*. Tissue dosage, although it should be expressed ultimately in rads (ergs per gram) is measured (up to 2 or 3 MeV) in terms of the

ionization caused in a small cavity of air situated, if possible, in the midst of the region under treatment. In superficial treatment, a small ionization chamber can be placed on the skin of the patient, and the skin dose measured directly. In deep therapy, it is as a rule impossible to imbed the chamber in the tissue and the depth dose has to be found by experiments with a *phantom*, that is, a medium which is the equivalent of tissue in its absorption and scattering.

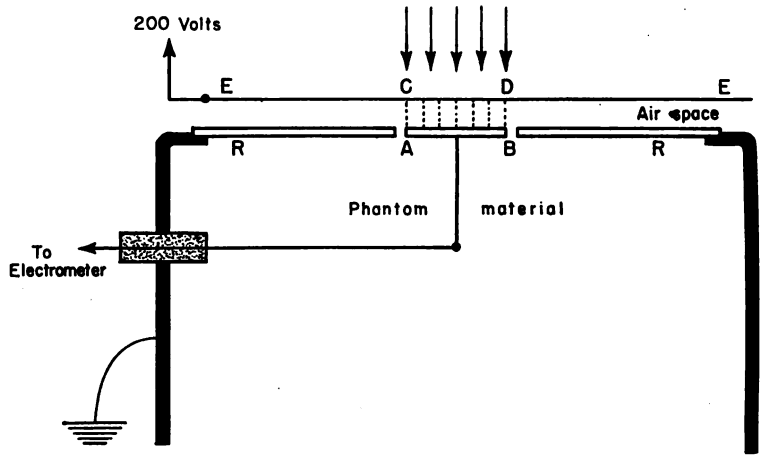


FIG. 11.13. To illustrate the basic principle of the Failla extrapolation ionization chamber. (Adapted from illustrations by Failla and Quimby.)

The magnitude of the skin dose is not the same as that measured at the same spot with the patient removed. At this stage the student will not be surprised at that statement, but it is so important that a reference to a simple experiment is not amiss. Suppose that at a certain place in air an operator has found that the intensity of an X-ray beam is $2r$ units per minute, and that he repeats his measurement with his ionization chamber resting on the skin of a patient, but without any other change. He finds that the second measurement indicates a greater intensity than $2r$ per minute. The reason for the increase has already been given in Chapter X. The primary beam gives rise to scattered rays in the tissue of the patient, and many of these—the *back scatter*—are scattered back into the ionization chamber, thus increasing the ionization. The correct skin dose must include back scatter.

Many measurements of skin dose have been made by the method given in the preceding paragraph, that is, with the ionization chamber

on the skin of the patient, but the results have shown that different types of chambers do not always agree. Some years ago a very careful study of back scatter was made by the radiological department of the Memorial Hospital, New York, under the direction of Mrs. Edith Quimby. It is worth while noting one or two features of a special ionization chamber utilized by Dr. Quimby in this study. The chamber, designed by Dr. Failla, of the Memorial Hospital, is a standard instrument, that is, one by means of which the dose in roentgens can be calculated from measurements of the ionization current and of the volume in which ions are produced. The essential features are shown in Fig. 11.13 which has been adapted from published illustrations by Dr. Failla and Dr. Quimby. Note the following.

(1) The X-ray beam passes vertically, not horizontally (as in the standard chamber of Fig. 11.4), *through* an upper electrode *EE*.

(2) This electrode, which is maintained at a potential of say 200 volts, consists of organic material like very fine net silk, or parchment, or pressdwood, made conducting by India ink or Aquadag.

(3) The lower electrode *AB*, to which ions go from the volume *ABCD*, and the surrounding guard ring *RR*, are parts of the same piece of material, like Lucite, whose upper surface has been made conducting by India ink, except for a narrow insulating ring around *AB*. The lower side of this whole piece, electrode and outer ring, is in contact with scattering material such as pressdwood or a mixture of rice and flour which acts as a phantom for human tissue.

(4) By means of micrometer screws, not shown in the figure, the upper electrode can be raised or lowered, so that readings may be taken for different thicknesses of the thin layer of air separating the upper and lower electrodes.

TABLE XXI

SKIN DOSE CORRESPONDING TO 100 ROENTGENS IN AIR

Quality h.v.l. in Copper	Area of Field in cm^2 5	25	100	400
0·035 mm.	110	117	124	128
0·3	114	124	134	147
1·0	114	124	136	149
2·0	109	117	126	136

Because of this feature, the instrument is called an *Extrapolation Chamber*. The idea was to measure the ionization per cubic centimetre for thinner and thinner air layers, as well as for upper electrodes of different thicknesses, and finally to extrapolate to find the ionization per c.c. for a negligibly thin layer in contact with the phantom, that is to evaluate a true measure of the skin dose. Actually it was found that for X-rays generated by 100 to 200 kilovolts, there was no change in the ionization per c.c. for air layers ranging from 0·5 to 3 mm and no difference between upper electrodes made of extremely thin silk and of parchment.

With such a chamber, the most careful measurements of surface dose were made and tables drawn up giving the correct skin dose corresponding to a specified number of roentgens in air, for a wide variety of conditions. A few actual numerical values, taken from the published work of Dr. Quimby, are given in Table XXI.

The numbers in the table show that the skin dose equivalent to 100*r* units in air varies with (1) the quality of the primary beam, and (2) the area of the field. For example, if we use always the same area, say 25 cm², the skin dose is 117 units for the softest rays, 124 for the next two more penetrating rays, but falls again to 117 for the most penetrating beam. This variation is due to change in scattering with changing quality.

On the other hand, if we use always rays of the same quality, those with an h.v.l. equal to 1·0 mm of copper, for example, we see that the equivalent skin dose steadily increases with increasing area, changing from 114 units for the smallest area to 149 for the largest. The increase with increasing field is due to the increased importance of scattered radiation. The larger the area, the greater the volume from which rays are scattered back to the chamber or to the area of skin under treatment.

For the same reason, if a thin portion of the body, such as a hand, is treated superficially, the back scatter is less for the same field, than for an area backed by a thicker portion of the body. In Table XXI the numbers are based on the assumption that there is enough underlying material to give maximum back scatter.

11.16. Depth Dosage. In therapy, the problem is generally that of treating diseased tissue below the skin. There are then two important problems: (1) how to effect a cure without injuring the skin and the healthy intervening tissue; and (2) how to measure correctly the *depth* dose delivered to the diseased tissue. We shall consider the second problem first.

TABLE XXII

NUMBERS OF ROENTGENS DELIVERED AT VARIOUS DEPTHS, FOR 100 ROENTGENS IN AIR. QUALITY OF RAYS GIVEN BY h.v.l. 1·0 mm IN COPPER

	5 cm²		25 cm²		100 cm²		400 cm²	
Depth	50 cm	70 cm	50 cm	70 cm	50 cm	70 cm	50 cm	70 cm
0	114	114	124	124	136	136	149	149
1	95	96	115	116	133	134	150	152
5	43	46	61	65	82	87	108	114
10	17	19	26	29	41	45	61	67
15	6	7	11	13	22	25	33	38

As already briefly mentioned, depth dose is measured indirectly by using *phantoms*, that is, materials equivalent to tissue in their absorption and scattering of X-rays. Water, rice, a mixture of rice and flour, ground meat, Columbia wax, lucite and pressdwood are all examples of fairly good phantoms. In taking the readings given in Table XXI, the special ionization chamber used by Mrs. Quimby was backed by a mixture of rice and flour. Similarly in evaluating the depth doses given in Table XXII, results also due to Mrs. Quimby, the chamber was embedded in a phantom of this kind. In this connection we quote Mrs. Quimby, " It is important that measurements used for determining tissue doses shall have been made in phantoms comparable in size with the part of the body undergoing treatment. The use of data obtained with large phantoms to specify doses in smaller portions of the body, such as the limbs or neck, may introduce errors because of the difference in the actual amounts of scattering materials in the two cases."

The measurements recorded in the above table were taken using 200 kV, constant potential rays, with an h.v.l. equal to 1 mm copper, after being filtered with 0·5 mm of copper. The 50 cm and 70 cm at the top of alternate columns give the distance from the target to the skin (or surface of phantom). It will be noticed that at the same distance below the surface the values of the depth doses are different for different target distances. At 10 cm depths, for example, with the 25 cm². field, the doses are 26 and 29 units. In all cases, a somewhat greater depth dose is delivered at the same depth in the case of the longer target distance. Since the greater the percentage of the surface dose delivered at the diseased tissue, the less the absorption by the intervening tissue, it is obviously an advantage to have as high a percentage depth dose as possible. Now calculations based on the

inverse square law, as well as the numbers in the above table, show that the greater the target-skin distance, the higher the percentage of the depth dose at any given distance below the surface.

It is easy to see how the inverse square operates. Suppose that *F* Fig. 11.14, is a source of radiant energy of any kind and that we com-

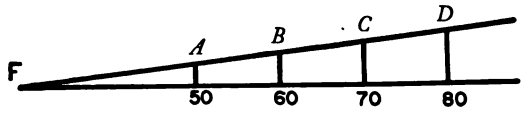


FIG 11.14. *F* represents the focal spot from which a narrow cone of rays spreads out.

pare the values of the intensity of the radiation at places *A*, *B*, *C*, *D*, which are 50, 60, 70 and 80 cm, respectively, from the source. If the intensity at *A* is 100 units, the intensity at *B*, provided there is no absorption between *A* and *B*, is $100 \times 50^2/60^2$, or 69·6 units; at *C* the intensity is $100 \times 50^2/70^2$, or 51·1 units; and at *D*, $100 \times 50^2/80^2$, or 39·1 units.

Hence, if we increase the distance from the source by 10 cm, the intensity falls to 69·6 per cent when we go from 50 cm to 60 cm, but to 39·1/51·1 or only to 77 per cent when we go from 70 cm to 80 cm.

As far as the inverse square law is concerned, it is, therefore, a distinct advantage to use large target-skin distances. On the other hand, the greater this distance, the smaller is the intensity of the X-ray beam, and hence the longer the time it takes to build up the required number of roentgens; that is, the longer the time of treatment in deep therapy. In choosing the most favourable target distance, a compromise must be made between the gain arising from the increase in percentage depth dose, and the loss due to increased time of treatment. In this connection we again quote Mrs. Quimby, " From a practical point of view, this increase in time is an important economic factor. From a biological aspect, it introduces complications because of differences in tissue recuperation." And, again, " it is not advantageous to use distances greater than ten or twelve times the known depth."

The student should realize that the numbers given in Table XXI and Table XXII are merely representative of a vast amount of data on depth dosage which has been accumulated. The publication in 1953 of a special supplement (No. 5) by the British Institute of Radiology on *Central Axis Depth Dose Data* will give some idea of the magnitude of the problem.

For extremely penetrating radiation, the maximum tissue dose occurs not at the surface but at an appreciable distance below. For example, according to data given by Johns, with 22 MeV rays

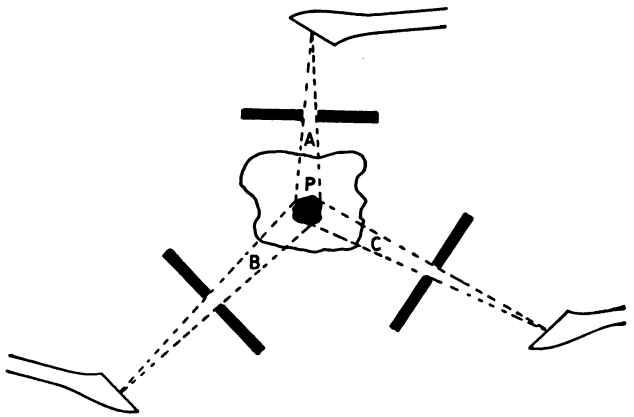


FIG. 11.15. To illustrate the method of cross-fire treatment.

generated by a betatron, the maximum, which is 15 per cent greater than the surface value, occurs at a depth of 4 or 5 cm. When ultra-penetrating radiation is used, it is customary to express depth dosage in terms of 100 at the maximum, not at the surface.

11.17. Rotational Therapy. The second and more important means of lessening the dose given to the skin and intervening tissue in deep therapy is illustrated by *cross-fire treatment*. The principle of this method is simple and will be clear after a glance at Fig. 11.15, where *P* represents a diseased region within the body treated through three *ports of entry*, at *A*, *B*, and *C*. If the desired dose is delivered in three parts, one through each port, the absorption by healthy tissue is reduced about one-third. Obviously more than three ports of entry can be used.

Rotational therapy is a logical extension of cross-fire treatment. In this, either the source of radiation or the patient is rotated in such a way that the central axis of the beam of rays always passes through the region under treatment. There are now on the market X-ray units in which the tube can be rotated through nearly, but not quite 360°, as well as be moved in other ways. When we are dealing with the use of a cobalt^{60} unit for therapy in section 15.8, reference will be made to a support containing the radioactive source which can be rotated through a complete circle.

Conversely, the source may be kept fixed and the patient rotated. At the Royal Marsden Hospital in London, for example, in connection with the therapeutic use of X-rays generated by a 2 MV Van de Graaff machine (see section 13.3), the patient is placed on a turntable which may be raised or lowered, as well as rotated. The beam of X-rays is directed at an angle to the axis of rotation and the patient may be in either a horizontal or a vertical position.

11.18. Grid and Sieve Therapy. A further means of protecting tissue between a deep-seated tumour and the surface consists in irradiation through a sheet of a substance like lead, of thickness 1 to 3 mm, in which opaque areas alternate with transparent, the sheet being placed on the skin of the patient. When the openings are longitudinal slits, the term *grid* is used ; if they are square or circular, *sieve* therapy should be used. Actual sieves used by Jolles, one of the research workers in this type of therapy, consist of squares, either 1×1 cm or $0{\cdot}5 \times 0{\cdot}5$ cm, the overall exposed area being as a rule equal to the protected area. Jolles and Mitchell have shown that when doses are fractionated in space in this way, large quantities of radiation may be administered to a tumour without untoward effects on the intervening layers of tissue. This type of irradiation promises to be of great value in helping to understand radiobiological processes and the role that undamaged tissue plays in repair processes.

11.19. Isodose Curves and Charts. The numbers in Table XXII give dosage values at distances below the surface for various depths *along the axis* of the primary beam, but, for any given depth do not apply to points away from the axis. Depth dosages at such points, that is, at any place throughout the irradiated region in a phantom can be measured readily by means of the ionization chamber. From such measurements charts like those shown in Fig. 11.16 can be constructed. In these charts a single curved line joins all points for which the dose is the same, hence the name *isodose curve*. The curves in this figure, reproduced through the courtesy of Dr. Edith Quimby, apply to the following set of conditions : X-rays generated by 180 kilovolts ; filter = 0·5 mm of copper ; target distance = 50 cm ; diameter of field at surface = 100 cm^2. A separate chart must be made, of course, for each set of conditions.

Given the appropriate conditions, if one knows the surface dose at the centre of the field, one can read off or quickly evaluate the correct corresponding dose at any point within the charted area. It will be realized that, although the chart depicts only a single plane, it

applies to the whole volume obtained by rotating it about the central axis.

11.20. The Roentgen and the Rad. The roentgen is essentially a unit of absorbed energy in air. It is now necessary to evaluate it in fundamental energy units and to relate it to the *rad*, the unit of

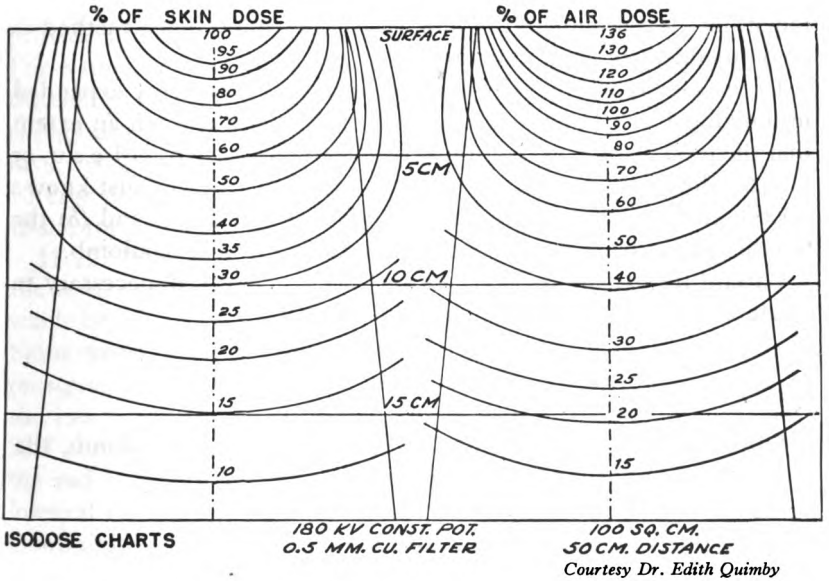


FIG. 11.16. Isodose charts for 180 kV constant potential, filter 0·5 mm copper ; 50 cm focal distance, field 100 cm².

absorbed dose recommended in 1953 by the International Commission on Radiological Units. In the recommendations of this body the absorbed dose of any ionizing radiation is defined as " the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest ". *The unit called the rad is by definition* 100 *ergs per gram.*

To find the relation of the roentgen to the rad it is necessary therefore to measure the mount of energy absorbed when X-rays fall on a mass of air or any other material. There are two ways of doing this : (*a*) by using an extremely sensitive calorimeter ; (*b*) by relating ionization to energy.

Since the energy resulting from ionization ultimately goes into heat, a direct and logical method is to measure the rise in temperature when a beam of X-rays or other ionizing radiation is absorbed in

a given mass of a material like lead, for example. However, the rise in temperature is so small, in one experiment by Laughlin and co-workers in the United States being of the order of 0·01° C.,* that this method has been of little practical use. It is worth noting, however, that in Handbook 55 issued by the U.S. National Bureau of Standards in connection with the highly energetic betatron and synchrotron radiations (see sections 13.9 and 13.10) the calorimeter method is recommended for such radiations.

In the second method the problem is to find the energy expended in ionizing 1 c.c. of air at n.t.p. (or 0·001293 gm) to such an extent that the total charge on the resulting ions (of either sign) is 1 e.s.u. or 1 statcoulomb. To calculate this amount of energy we must know : (*a*) the energy expended in creating a single ion pair ; and (*b*) the number of ion pairs corresponding to a charge of 1 statcoulomb.

Careful investigations have shown that the energy W necessary to create a single ion pair is 32·5 electron-volts† or

$$\frac{32{\cdot}5 \times 4{\cdot}8 \times 10^{-10}}{300} \text{ erg} \quad \text{or} \quad 5{\cdot}2 \times 10^{-11} \text{ erg.}$$

Since the charge on a single ion is $4{\cdot}80 \times 10^{-10}$ statcoulomb, the number of ions carrying a total charge of 1 statcoulomb is

$$\frac{1}{4{\cdot}8 \times 10^{-10}} \quad \text{or} \quad 2{\cdot}08 \times 10^{9}.$$

Therefore the energy necessary to ionize 0·001293 gm of air is equal to $5{\cdot}2 \times 10^{-11} \times 2{\cdot}08 \times 10^{9}$ or 0·108 erg.

Hence 1 roentgen corresponds to an energy absorption of 0·108 erg per 0·001293 gm of air, or

$$1r = \frac{0{\cdot}108}{0{\cdot}001293} = 83{\cdot}7 \text{ ergs per gram of air.} \qquad (1)$$

(Recall that 1 calorie $= 4{\cdot}2 \times 10^{7}$ ergs.)

For aqueous tissue, the energy equivalent of 1 roentgen varies with the wave length, but for gamma rays, $1r = 93$ ergs‡ per gram.

* The heat resulting from 50,000r delivered to 1 gram of soft tissue is about 0·1 calorie.

† 34eV is probably (1955) a better mean value for W, whose magnitude varies slightly with different ionizing particles. In 1953 the International Commission recommended that for W and another quantity s (see footnote below) " tables of the best available data be prepared and held under continual review ".

‡ E_m, the absorbed energy per gram in any medium can be calculated from the absorbed energy per gram in air using the relation $E_m = s_m E_a$, where s_m is the ratio of the mass stopping power of the medium to that of air.

Since 1 rad = 100 ergs per gram,
for air 1 roentgen = 0·837 rad,
for soft tissue 1 roentgen = 0·93 rad, for very hard radiation.

11.21. R.E.P. Now that the rad has been adopted as an energy unit for all ionizing radiations, the *roentgen-equivalent-physical* (r.e.p.) is scarcely necessary because it was originally adopted to provide a convenient unit of absorbed dose for particle radiations. For a time, it was such a dose that for any radiation or any medium the energy absorption per gram is 84 ergs, that is, the equivalent of the energy absorption of 1 gram of air when exposed to X- or gamma rays. According to Spiers, it is now customary to use the value of 93 ergs per gram, the equivalent of the absorption of 1 gram of soft tissue for gamma rays. (See also Appendix A.)

11.22. Integral Absorbed Dose. Sometimes we wish to know the total energy absorbed by an extended region, possibly even the whole body. In such a case we speak of the *Integral (Absorbed) Dose.* Some years ago Mayneord suggested that the unit be the *gram-roentgen.* For example, if 0·5*r* was delivered to a mass of 12 grams, the integral dose would be 6 gram-roentgens. Since for air, 1*r* = 83·7 ergs per gram, 1 gram-roentgen for air = 83·7 ergs. Now that the rad has been introduced as a unit of absorbed dose, the unit of integral dose recommended by the Commission is the *gram-rad* or 100 ergs, and Mayneord's unit is scarcely necessary.

11.23. Energy Flux and the Roentgen. In section 11.3 it was emphasized that the student must distinguish carefully between the energy incident on the surface of a medium and the resulting absorbed dose. We wish now to establish the relation between energy flux and the roentgen.

Let *ABCD*, Fig. 11.17, represent a section or slice of air whose faces *AB* and *CD* have each an area of 1 cm² and whose thickness $AC = BD = x$ is extremely small.

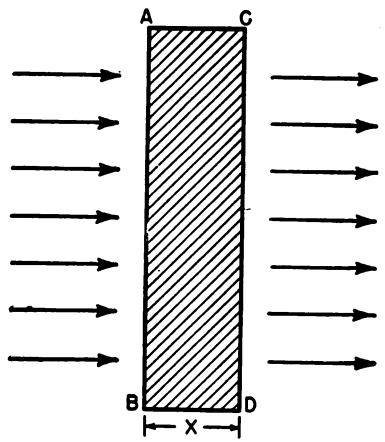


FIG. 11.17. *ABCD* represents a thin section of absorbing material traversed by X-rays.

Suppose when a flux of X-rays of magnitude E_f ergs per cm² is incident on the face *AB*, the resultant dose is *r* roentgens. Then, if

the mass of this slice of air is m grams, from relation (1) above we have

$$\text{the energy absorbed} = 83{\cdot}7r \,.\, m \text{ ergs.} \tag{2}$$

But $\quad$ the energy absorbed $= E_f \times$ fraction absorbed.

Therefore, $\quad E_f \times$ fraction absorbed $= 83{\cdot}7r \,.\, m$ ergs.

Now it follows from relation (6) in section 10.12 that when a beam of X-rays is absorbed by a *thin* layer of a medium

$$\text{the energy absorbed} = E_f \mu x,$$

where μ is the absorption coefficient. In this case, since it is more convenient to use $\frac{\mu}{\rho}$, the mass absorption coefficient, we write

$$\text{absorbed energy} = E_f \,.\, \frac{\mu}{\rho} \,.\, \rho x$$

$$= E_f \,.\, \frac{\mu}{\rho} \,.\, m, \tag{3}$$

since the volume of the slice of air $= x \,.\, 1$ and the density is ρ grams per c.c.

Equating (2) and (3) we have

$$E_f \,.\, \frac{\mu}{\rho} \,.\, m = 83{\cdot}7r \,.\, m$$

or

$$E_f \,.\, \frac{\mu}{\rho} = 83{\cdot}7r. \tag{4}$$

If we deal with wave lengths for which pair production can be neglected,

$$\frac{\mu}{\rho} = \frac{\sigma_a}{\rho} + \frac{\tau}{\rho},$$

and relation (4) can be written

$$E_f\left(\frac{\sigma_a}{\rho} + \frac{\tau}{\rho}\right) = 83{\cdot}7r$$

or

$$E_f = \frac{83{\cdot}7}{\frac{\sigma_a}{\rho} + \frac{\tau}{\rho}} \text{ ergs per cm}^2 \text{ per roentgen.}$$

For example, using the appropriate coefficients we find, for $\lambda = 0{\cdot}1$ A, $E_f = 3{\cdot}4 \times 10^3$ ergs per cm^2 per roentgen; for $\lambda = 0{\cdot}2$ A, $E_f = 2{\cdot}4 \times 10^3$; and for $\lambda = 0{\cdot}4$ A, $E_f = 0{\cdot}54 \times 10^3$. The very much smaller value of E_f for the long wave length is of course due to the increased absorption of the softer rays.

Calculations made by Mayneord for ultra-penetrating radiation, show that, whereas for quantum energies ranging from 0·1 to 1 MeV the value of E_f does not depart markedly from 3,000 ergs per cm² per roentgen, above 1 MeV its value rises until at 10 MeV it is nearly twice as great. But, as we have seen, at these high energies, the roentgen ceases to be of much value.

PROBLEMS AND QUESTIONS

1. (*a*) Make a diagram showing the electric connections when a standard ionization chamber and a galvanometer are used to compare the dose-rates of X-ray beams.

(*b*) If in a standard chamber ions were taken from a volume of 10 c.c. and a current of 10^{-9} ampere was recorded by a galvanometer, what is the dose-rate of the beam in *r* units per second?

2. Why must a small ionization chamber be calibrated by means of a standard chamber if measurement in *r* units is required?

3. How does the intensity of a beam of X-rays at a given place depend on (i) the distance from target, (ii) the voltage across the tube, (iii) the tube current?

4. When a small ionization chamber (joined to an electroscope) is placed in a beam of X-rays at a place 25 cm from the focal spot, the electroscope falls at the rate of 2·1 divisions per second. What is the rate of fall if the chamber is removed to a distance of 60 cm? *Ans.* 0·36 div. per sec.

5. A steadily increasing voltage is applied to two plates between which a narrow strip of air is kept ionized by a beam of X-rays of constant intensity. Describe, with simple graph and explanation, how the current between the plates alters with the voltage.

6. How would you show experimentally that water is a good phantom for tissue?

7. A small ionization chamber is used to measure the intensity of an X-ray beam at a certain focal target distance, (i) in air, (ii) when the chamber rests on a thick block of paraffin, (iii) when the chamber is completely surrounded by paraffin. Intensities of 28, 43, and 35 units are obtained. Discuss and explain these results.

8. Describe an experiment to show that in deep therapy, scattered rays may be the cause of a greater intensity at the place treated than the primary beam.

9. The natural leak of an electroscope of capacity 10 statfarads is 0·5 division per minute. Find the natural leak, if the insulated plate of a condenser of capacity 200 statfarads is attached to the insulated system of the electroscope, the outer case of the electroscope and the other plate of the condenser being grounded. *Ans.* 0·238 div. per min.

10. In a standard ionization chamber, ions are driven to a collecting electrode from a volume of 10 c.c. The capacity of the electrode and attached electrometer system is 800 statfarads. If the dose-rate of the X-ray beam is 0·4*r* units per second, find the change of potential (in volts) of the electrometer system in 5 minutes. (1 farad $= 9 \times 10^{11}$ statfarads.) *Ans.* 450 volts.

11. Make a diagram showing how a small ionization chamber can be used in connection with an electroscope. Indicate what parts are insulated and what grounded.

12. An electroscope is joined to the insulated plate of an X-ray standard parallel plate ionization chamber (whose other plate is grounded) and the insulated system, whose capacity is 1/1,000 microfarad, is charged until its potential is 900 volts. (i) What is the total charge in coulombs on the insulated system? (ii) A parallel beam of X-rays passes between the plates of the chamber and ions are driven to the insulated plate from a volume of 30 c.c. If the dose-rate in the chamber of the beam of X-rays is $\frac{1}{2}$ roentgen per second, find how long it will take to discharge the electroscope (and attached plate).

1 microfarad = 900,000 statfarads ; 300 volts = 1 statvolt ;
1 coulomb = 3×10^9 statcoulomb.

Ans. (i) 9×10^{-7} coulomb ; (ii) 3 minutes.

13. In an ionization chamber, why must the voltage between the two electrodes exceed a certain minimum amount?

14. Explain what constitutes a good " phantom " for X-rays in therapy, and name one suitable substance.

15. In deep therapy why is a filter always used between the patient and the target of the tube?

16. A tumour 10 cm below the surface is treated under the following conditions : Port of entry = 25 cm ; Voltage across tube = 200 kV ; Tube current = 5 ma ; Filter = 0·75 mm Cu + 1 mm Al ; Target-skin distance = 30 cm ; Effective wave length = 0·15 A ; Percentage of surface dose = 40 per cent. Discuss the importance of each factor.

17. Discuss the importance of the size of the port of entry in using X-rays for therapy.

18. Make a diagram showing how a thimble ionization chamber might be used in conjunction with an electroscope for comparing X-ray dose-rates. Give two reasons why such an arrangement does not necessarily allow you to evaluate dose-rates in *r* units per second.

19. Describe briefly, listing successive steps, the use of the Victoreen condenser meter for measuring an X-ray dose in roentgens.

20. What condition must be fulfilled, if an ionization chamber is to be described as " air-wall "? How is this conditon obtained practically?

21. How would you show experimentally the existence of " back scatter "?

22. The volume in which ions are produced by an X-ray beam in a standard ionization chamber is 20 c.c. If the dose-rate of the beam in the chamber is 0·4*r* per second, find how many ions (of either sign) go to the collecting electrode in 1 minute.

23. Why is the skin dose corresponding to a certain air dose (i) greater than the air dose ; (ii) greater for a beam of large aperture than for one of small aperture?

24. Why is the t.e.d. (expressed in *r* units on the skin) greater for wave length 0·2 angstrom than for 0·25 angstrom?

25. In a standard ionization chamber, ions are driven to a collecting electrode from a column of 10 c.c. and the capacity of the electrode and attached electrometer system is 10^{-9} farad. When a certain X-ray beam

traverses the chamber, the potential of the electrode and attached system changes at the rate of 2 volts per second. Find the dose-rate in the chamber of the beam in *r* units per second.

26. A condenser ionization chamber, with air-wall, has a volume of 4 c.c., a capacitance of 3 e.s.u. (statfarads) and is initially charged to 200 volts. After being carried by a radiologist for a week, the residual potential is 80 volts, but when kept in a lead container for the same time, the residual potential is 185 volts. Calculate the dose in roentgens received by the radiologist during the week. *Ans.* 2·6*r*.

27. A certain Victoreen instrument consists of: (*a*) a condenser chamber, with air-wall, of capacitance 80 e.s.u. and of air volume 0·8 c.c.; and (*b*) a leak-free string electrometer of capacitance 320 e.s.u. The instrument is charged in the usual way to a potential of 360 volts. The chamber is removed, exposed to 100*r* of hard gamma rays and then inserted in the instrument. Find the new potential of the fibre. *Ans.* 300 volts.

28. An ionization chamber of volume 0·5 c.c. and capacitance 50 e.s.u., with air equivalent walls, is used in connection with an electrometer of capacitance 10 e.s.u. as in a Victoreen instrument. The instrument is charged initially to a potential of 200 volts and the chamber used to measure the output rate of an X-ray tube. Calculate the rate if, after 30 seconds exposure of the chamber, the electrometer indicates 125 volts when the chamber is reinserted in the instrument. *Ans.* 1*r* per sec.

29. A Victoreen type of dose-meter has a condenser chamber of capacitance 40 e.s.u. and an electrometer of capacitance 10 e.s.u. The air volume of the chamber is 1 c.c. (*a*) The chamber is exposed to 45*r* of hard radiation for which the chamber is air wall. The air pressure is 760 mm Hg and the temperature 37° C. Find the charge lost by the condenser and the voltage change indicated by the electrometer. (*b*) The instrument is now recharged to 400 volts and the chamber exposed to 45*r* of soft radiation. The new potential when the chamber is reinserted is 150 V. What conclusion do you draw?

30. A condenser ionization chamber, with air equivalent walls and a volume of 0·5 c.c., is used at n.t.p. in the same manner as a Victoreen dose-meter to measure the output of an X-ray tube. The scale of the associated electrometer is graduated in volts and the instrument is initially charged to 250 V. The chamber is then exposed for 30 seconds in the X-ray beam. When it is reinserted in the instrument the reading on the electrometer scale is 167 V. If the capacitance of the condenser is 37·5 e.s.u. and that of the electrometer 7·5 e.s.u. find the output rate of the tube. *Ans.* 0·83*r* per sec.

31. If it requires 32·5 eV to produce an ion pair in air, find the energy in ergs absorbed per c.c. of air at n.t.p. per roentgen. *Ans.* 0·108 erg.

32. Given that the energy absorbed in soft tissue is equal to 93 ergs per gram per roentgen and that for a given wave length the energy flux per cm^2 per roentgen is 3,000 ergs, find the effective mass absorption coefficient for soft tissue for this wave length. *Ans.* 0·031 cm^2 per gm.

CHAPTER XII

NATURAL RADIOACTIVITY

12.1. The Discovery of Radioactivity. The middle of the last decade of the nineteenth century was one of the most fruitful periods in physical science which has ever existed. Within two or three years, the electron, X-rays, and radioactivity were all discovered. These were by no means independent discoveries because in science, as in life, one thing often leads to another. A good example of this is found in the discovery of radioactive substances. The walls of gas X-ray tubes strongly fluoresce and in the early days it was not unnatural to associate the origin of these invisible rays with the fluorescence. With this idea in mind, Becquerel, a French scientist, tried to see if certain compounds of the element uranium would emit X-rays after being made to fluoresce by exposure to light. He was rewarded by finding an invisible radiation, but was soon able to show that it had nothing to do with X-rays. The uranium compound in its normal state, that is, without any stimulus by light or by anything else, was found to emit something which passed through a sheet of black paper and affected a photographic plate behind the paper. This emission, moreover, was perfectly spontaneous. Neither heat nor cold could start or stop it. It was a natural property of the compound.

This original discovery made in 1896 was followed by rapid developments and it was not long before it was found that residues of pitchblende, one of the ores in which uranium is found, were much more radioactive than pure uranium compounds themselves. In 1898 Madame Curie, the Polish wife of a French physicist, with the assistance of her husband, isolated *polonium* and *radium*, two substances possessing radioactive powers in a remarkably high degree. Radium was shown to be an element of atomic weight 226 with chemical properties similar to the stable element barium.

It is, however, with the nature of radiations emitted by a radioactive substance that we are specially concerned, not with its chemical properties. The radiations, whatever they are, have three outstanding properties. They ionize the air, or any gas, through which they pass ; they effect a photographic plate like light or X-rays or positive rays ; and they cause fluorescence when they strike certain substances.

The ionization effect will detect such a small quantity of radioactive substance that it has been of great importance throughout the whole development of the subject; the photographic effect led to Becquerel's discovery; and the ability of the rays to excite fluorescence is probably familiar to most people because of the radium-coated watch hands which may be seen in the dark.

12.2. The Nature of the Radiations. In seeking to find out the nature of the radiations emitted by a substance like radium, it was natural that early investigators should examine what happens when the rays traverse a magnetic field. The deflection of cathode rays by a magnetic field had shown that they were negatively charged particles. What did such a test show when radioactive radiations were examined? In principle the experiment is extremely simple. A narrow beam of rays emerging through the top of a containing box *B*, Fig. 12.1, passes through a magnetic field between *N* and *S*. By such a means the original beam is separated into three components: (1) a portion undeflected by even the strongest magnetic field; (2) a second part readily deflected in the direction which indicates that it must consist of negatively charged particles; and (3) a third part, consisting of positively charged particles, deflected a slight amount in the opposite direction by sufficiently strong fields. The positive particles are called *alpha* rays, the negative *beta*, and the undeflected beam, which is of a non-corpuscular nature, *gamma* rays.

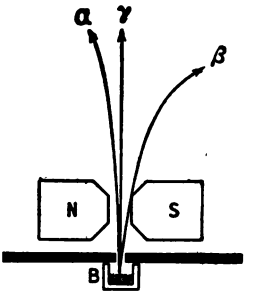


FIG. 12.1. A magnetic field separates the radiations from radium into three groups. The deflection of the β beam is towards the observer, of the α beam away from him.

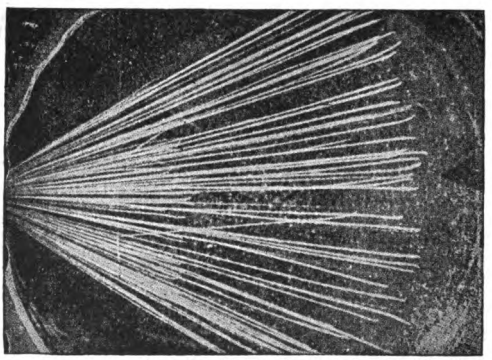
Once we know that we are dealing with a flight of particles, certain questions at once suggest themselves. What is the mass of each of these particles? What charge do they carry? How fast do they move? How penetrating are they? As always, experiment provides the answer to these questions. In the following sections, important details are given concerning each kind of radiation.

12.3. Alpha Rays. (1) As already noted, alpha rays are positively charged particles. Experiment shows that the magnitude of the charge carried by each particle is equal to two electronic units, that is, it is exactly twice the charge on a proton.

(2) Measurements of the amount of the deflection produced by magnetic and electric fields (see section 3.5), combined with a know-

ledge of the magnitude of the charge, show that each alpha particle has a mass about four times that of a hydrogen atom. Combining (1) and (2) we see that this particle is essentially an atom of atomic weight 4 and atomic number 2.

(3) Alpha rays cause intense ionization as they traverse a gas. This is beautifully shown by cloud track photographs (see section 10.5), such as are reproduced in Fig. 12.2 and Fig. 12.3. In Fig. 12.2 each white line represents the path of a single alpha particle. In its flight it causes such intense ionization that the little droplets formed on ions are so close together that they give rise to an unbroken continuous streak of light. The *specific ionization*, that is, the number of ion pairs per unit length of path, for an alpha particle is on the average about 3,000 per mm.



Courtesy N. Feather and the Royal Society

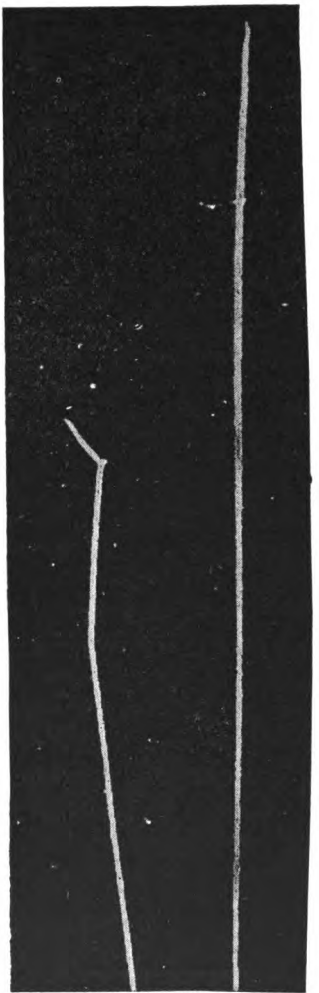
FIG. 12.2. Cloud track photograph showing a shower of alpha particles ejected from a small source.

The photograph of Fig. 12.3 shows the tracks of but two alpha particles. In the left hand track of this figure it will be noted that the path turns through a small angle to the right, and then just before the end of the track, it makes a second and much sharper turn to the left. These sudden turnings are evidence of the near approach of the alpha particle to the nucleus of an atom. Ordinarily this heavy particle ploughs along without being deflected out of its path even when passing right through an atom. Occasionally, however, the particle in its passage through the atom passes so near the nucleus that its direction is altered as shown in the photograph. The study of such deflections, that is of *scattering*, when alpha rays strike a thin sheet of gold, led to estimates of the size of the nucleus, and to the picture of the atom we have given in section 3.6.

On rare occasions an alpha particle strikes a nucleus "head-on", and

in such cases things happen, as we shall see later. (See section 12.21.)

Tracks of particles may also be revealed by the use of the photographic emulsion on a plate or film. If, for example, an alpha particle traverses such an emulsion, on development of the plate or film its track is readily visible. Since the tracks of such particles in emulsions are extremely short, the photographic reproduction is usually highly magnified. A good example of such an alpha ray track is seen in the left side of Fig. 14.2, the reproduction of a photograph kindly given the author by Dr. Pierre Demers, of the University of Montreal.



Courtesy C. T. R. Wilson and the Royal Society

FIG. 12.3. Cloud track photograph of paths of two alpha particles.

(4) When they strike certain substances, alpha rays cause marked fluorescence, a property which is made use of in the spinthariscope, one of the early radioactive toys. In this arrangement, a speck of radioactive material is placed near a screen coated with zinc sulphide and, with eyes rested, the screen is viewed through a magnifying glass in a darkened room. Little flashes of light are seen to dance about in irregular fashion, somewhat as if in a patch of sky the stars kept disappearing in one place and reappearing in another. Each scintillation corresponds to the impact of an alpha particle on the screen. We have called this a toy but, as a matter of fact it was the basis of more than one investigation in which the number of alpha particles leaving a source in a given time was counted, and it was used with success in determining how far both alpha particles and protons travel before they are no longer able to ionize.

A much more important application of the fluorescent effect of alpha particles and other radiations is found in the scintilliaton counter, explained in section 12.9.

(5) Alpha rays have a speed which varies with the radioactive source from which they are emitted, but for the most part is between one fifteenth and one tenth of the velocity of light. It is worth noting that alpha particles, whose speed is a little less than one twentieth of the velocity of light, have about four million electron volts (4 MeV) of energy. Alpha particles are emitted from some sources with energies as high as 8 MeV. In Fig. 12.2 it will be noted that the tracks come to an abrupt end. This is due to the fact that once the velocity falls below a certain value, an alpha particle is no longer able to ionize. The actual range in air over which they can ionize is only a few centimetres, never more than 8·6 cm. In water the maximum range is of the order of 0·06 mm.

(6) It follows from this that alpha rays are readily absorbed by solids. They are completely cut off by a sheet or two of ordinary paper, or by a thickness of about 0·006 cm of aluminium, and they cannot get through 0·1 mm of epithelial tissue. It will be evident, therefore, that if a radioactive substance is enclosed in a glass tube (unless extremely thin), alpha rays will not get through the glass.

Stopping power of a medium for an alpha particle (or for any other ionizing particle) is measured by the energy lost by the particle per unit path distance. The *atomic stopping power* is the average energy loss per atom. The *relative stopping power*, a quantity frequently used, is the ratio of the atomic stopping power of the medium to that of air.

To examine the alpha ray emission from a substance, an electroscope of the type shown in Fig. 12.4 is used. The insulated rod of an electroscope extends, through insulating material, into the lower chamber, where it is attached to a disc *D*. The radioactive material, placed on the earthed platform, gives off radiations which ionize the air in its vicinity. When the electroscope is charged, the leaf falls at a rate which is proportional to the amount of ionization, and hence to the quantity of radioactive material.

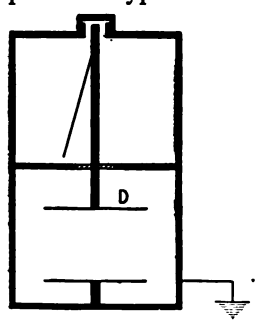


FIG. 12.4. An alpha ray electroscope.

12.4. Beta Rays. (1) Beta rays are nothing but high speed electrons shot out of the nuclei of atoms of radioactive substances with velocities which cover a wide range, but may exceed nine tenths of the velocity of

light. To acquire a speed equal to the fastest beta ray—over ninety-nine per cent of the velocity of light—a cathode ray would have to fall through a potential difference of over three million volts.

(2) Beta rays ionize a gas, although not so intensely as alpha rays. The difference will be evident by a comparison of Fig. 12.5. with either Fig. 12.2 or Fig. 12.3. In Fig. 12.5 the straight line of tiny dots marks the path of a beta ray moving so quickly that it is not deflected out of its path. On the same photograph the curved irregular path near the middle is due to a slow electron which is easily turned aside by collisions. The student should also examine Fig. 13.14, where the photograph shows very beautifully the curved path of an ionizing particle like a beta ray or an electron when it is constantly deflected by the presence of a magnetic field. By way of comparison with an alpha particle, note that a beta ray creates from 10 to 20 ions per millimetre of its path.

The type of electroscope shown in Fig. 7.1 may also be used for studying beta ray ionization. If the radioactive material is placed outside the window *W*, a moderate thickness of paper will exclude alpha rays. Alternately, the window can be removed, the metal wall of the container being continuous, and the chamber can be designed so that a tray containing the radioactive material can be placed inside, at the bottom. Here again, a sheet of paper of suitable thickness can be used to remove the alpha rays.

Courtesy C. T. R. Wilson and the Royal Society

FIG. 12.5. Cloud-track photograph of a fast beta-ray. The irregularly curved line of dots arises from a slowly moving electron.

(3) Beta rays, being of small mass and of high speed, are much more penetrating than alpha rays. The fastest will pass through several millimetres of a low density metal or of tissue, and traverse as much as ten feet of air before they are stopped. They are,

however, completely stopped by less than 0·5 mm of gold or of platinum, or by about 0·4 mm of steel or monel metal.* It will be seen then, that, by placing a radioactive substance in a suitable container it is not a difficult matter to remove both beta and alpha rays.

12.5. Gamma Rays. (1) Gamma rays are electromagnetic waves of the same nature as X-rays, but for the most part of shorter wave length. The actual values of emitted wave lengths depend on the radioactive source, and for a given source more than one wave length is emitted. From radium C, for example (see section 12.17), there are waves as long as 0·2 angstrom, a value in the therapy X-ray range and as short as 0·0056 angstrom.

It is more customary to describe a particular kind of gamma ray by giving, not its wave length, but the corresponding photon energy. Thus cobalt^{60} emits two groups of gamma rays, one of photon energy 1·17 MeV, the other, 1·33 MeV. By measuring the energies of the different gamma rays emitted by a radioactive nuclide, information is obtained about the nucleus of the emitting atom. A nucleus may exist in different energy states or levels, a gamma ray being emitted when there is a transition from a higher to a lower level. (See Fig. 15·5.)

(2) Some gamma rays are so penetrating that a thickness as great as 10 cm of lead will not completely absorb them. A thickness of platinum or of gold equal to 0·5 mm, which we have seen completely absorbs beta rays, absorbs only about 7 per cent of the gamma rays emitted from a salt of radium enclosed in a tube. Muscular tissue, 2 cm in thickness, reduces the intensity only 5 per cent, and even after traversing 20 cm, the rays emerge with over 60 per cent of their original intensity.

As with X-rays, the actual absorption coefficient varies with the wave length but an average value enables the radiologist to estimate with sufficient accuracy for most purposes the absorption caused by various materials. In this connection the numbers given in Table XXIII† are useful.

The coefficients given in this table are used in the same way as the linear absorption coefficients of X-rays as explained in section 10.10, with the exception that, when using the values given in Table XXIII the thickness of the absorbing layer must be expressed in millimetres,

* For exact examination of the penetration of beta rays, use is made of absorption coefficients, and the relation $I = I_0 e^{-\mu x}$ as in X-rays.

† Taken from Radium Dosage, Bulletin No. 17 of the National Research Council of Canada. By G. C. Laurence.

TABLE XXIII

ABSORPTION COEFFICIENTS FOR GAMMA RAYS FROM RADIUM

Substance	Coefficient
Aluminium	0·007
Lead	0·088
Platinum	0·139
Gold	0·140
Monel	0·021
Brass	0·020
Muscle	0·0024
Epithelial tissue	0·0024
Bone	0·0055
Water	0·0026
Paraffin wax	0·0022

not centimetres. Thus if I_0 is the intensity of the gamma radiation from a radium salt incident on a layer of aluminium x mm thick, I, the emergent intensity, is given by the relation

$$I = I_0 e^{-\mu x} = I_0 e^{-0\cdot007x},$$

or, by the equivalent relation

$$\mu = 0\cdot007 = \frac{2\cdot30}{x}(\log_{10} I_0 - \log_{10} I).$$

If the thickness of the absorber is small, these relations may be replaced, with very slight error, by the simpler expression

$$I = I_0(1 - \mu x),$$

from which it follows that the

$$\textit{fraction absorbed} = \mu x.$$

For example, 1 mm of aluminium absorbs about 0·007 or 0·7 per cent of the incident gamma radiation from a radium source; 0·5 mm of gold about $0\cdot140 \times 0\cdot5$ or about 7 per cent; 0·25 mm of platinum about 3·5 per cent; and 1 mm tissue about 0·24 per cent.

(3) Being of the same nature as X-rays, gamma rays ionize a gas through which they pass and cause an emission of secondary electrons, sometimes called secondary betas, when they traverse matter. The general absorption processes have been explained in section 10.7. As with very penetrating X-rays, the reduction in intensity of a primary beam is due in part to scattering, the amount depending on the quality of the beam and the nature of the material, and in part to true absorption. The coefficients given in Table XXIII take into

account both these factors. True absorption is due to the three factors listed in section 10.7. For gamma rays of low energy and for heavy elements, the photoelectric emission of electrons is of importance; for more energetic rays up to 1 MeV, particularly for light elements, the secondary electrons are almost entirely recoil; and for rays with energies of several MeV pair production becomes important.

Secondary electrons may have velocities high enough to enable them to pass through many metres of air or a few millimetres of tissue. This means that, when a radium salt is enclosed in a tube like platinum, of sufficient thickness to absorb completely the original beta rays, that is, the *primary* betas, the gamma rays will cause an emission of secondary betas from the platinum. In radium therapy it is therefore necessary to surround the metal with a secondary filter of such a material that it absorbs the objectionable secondary betas, and does not emit intense secondary beta rays itself. For this purpose, a material like rubber has been used to a considerable extent, although recently Quimby and co-workers have shown that " the secondary radiation is considerably less for substances of intermediate atomic number than for those toward either end of the atomic scale ". Stainless steel or nickel, for example, are sometimes more suitable than rubber or celluloid.

As with X-rays, if a beam of gamma rays is used for the treatment of deep-seated tumours, the scattered rays from surrounding tissue add to the dose delivered to the tumour. It should be recalled also that, because of the true absorption due to the Compton effect, the wave length of gamma radiation is increased after scattering, that is, the beam is softened.

(4) The electroscope illustrated in Fig. 7.1 (with window replaced by metal) may be used conveniently for studying the relative intensities of the gamma radiations from two sources, provided that the thickness of the walls of the chamber is sufficient to absorb all the primary beta rays from the sources.

12.6. Internal Conversion Electrons. The emission of beta rays from radioactive nuclei should not be confused with an emission of so-called *conversion electrons*. Sometimes a gamma ray photon gives up its energy to an orbital electron of the atom in whose nucleus it originated, with the resulting ejection of the (conversion) electron. This process is followed by the emission of characteristic X-rays, after the manner described in section 8.10.

Auger Electrons. Characteristic X-rays themselves are sometimes absorbed in the very atoms in which they originated, their

energy being used to eject orbital electrons. Electrons emitted by this kind of auto-ionization process are called *Auger*.

Electron Capture. A radioactive decay process may take place in which the nucleus captures an electron from a K (or an L or an M) shell. This process is also followed by the emission of characteristic X-rays.

12.7. Geiger-Mueller Counters. In section 12.3 a brief reference was made to an experiment in which the number of alpha particles leaving a source was counted by making use of scintillations. A much better method is provided by the use of an electrical counter, a device which has the additional advantage that it can be used for many other purposes, some of them of great importance in radiology.

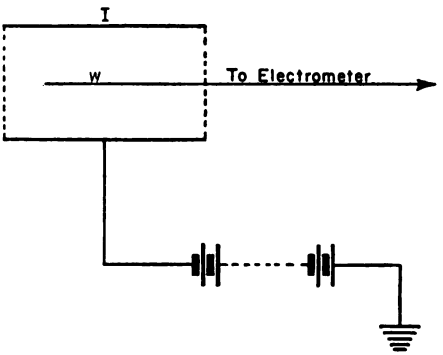


FIG. 12.6. *I* represents an ionization chamber with central electrode *W* joined to an electrometer.

Fundamentally counters make use of ionization and ionization chambers. To understand the basic principles, consider the specific problems of (*a*) detecting by an electrical method the entry of a single alpha particle into an ionization chamber, and (*b*) of counting the number which enter in a given time. Suppose an alpha particle enters an ionization chamber *I*, Fig. 12.6, consisting of an outer conducting cylinder maintained at a high negative potential and a central electrode *W* joined to a simple electrometer. As has been indicated, an alpha particle on the average creates some 3,000 ion pairs per millimetre of its path in air at atmospheric pressure. Therefore, if its ionizing path in the chamber is, say 5 cm, it will create $3{,}000 \times 50$ or $1{\cdot}5 \times 10^5$ ions. If we assume no recombination, $1{\cdot}5 \times 10^5$ particles, each with the electronic charge of $4{\cdot}80 \times 10^{-10}$ statcoulomb, will be driven to the central electrode, that is, it and the attached electro-

meter will acquire a negative charge of $1{\cdot}5 \times 10^5 \times 4{\cdot}8 \times 10^{-10}$ or about $6{\cdot}4 \times 10^{-5}$ statcoulomb.

Since the capacity of the system acquiring this small charge is small, the resulting change in potential is of the order of millivolts or even less. With an ordinary type of electrometer such a potential pulse, as we may call it, would not be observed. On the other hand, by joining the collecting electrode to a suitable vacuum tube circuit, for example, to the grid of an FP54 tube, the arrival of the pulse due to the entrance of an alpha particle into the chamber can be registered and observed.

Now, suppose a succession of alpha particles enters a chamber, possibly a large number per second. What arrangement can be made to obtain a corresponding number of observable electrical changes per second? The answer to that question was first given in 1908 by Rutherford and Geiger, long before the days of electronic devices. Suppose that the voltage applied between the collecting electrode and the outer case of the chamber is made sufficiently high that the ions or electrons in their passage through the strong electric field near the electrode acquire enough energy to ionize by collision. In that case,

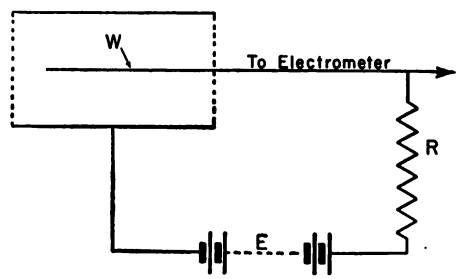


FIG. 12.7. When a large ionization current develops suddenly in the ionization chamber, because of the drop in potential along the resistance R, the p.d. between the electrode W and the chamber wall drops suddenly.

each original electron or ion creates many more, because each of the second generation is speeded up to ionize by collision, the process being rapidly cumulative, so that the original $1{\cdot}5 \times 10^5$ ions is multiplied many times. Under such conditions, the pulse of potential given to the fibre of a string electrometer attached to the collecting electrode is great enough to be observed. This was the principle employed by Rutherford and Geiger who stated that " the current through the gas due to the entrance of an alpha particle into the detecting vessel was magnified . . . sufficiently to give a marked

deflection to the needle of an electrometer of moderate sensitivity". Their "detecting vessel" was the parent of the modern counter.

In order to count a rapid *succession* of alpha particles, the cumulative discharge in the chamber following the entrance of a single particle must be quenched in a very short time. Obviously the shorter the time, the more rapid the counting which can be made. This book is not the place to go into details regarding quenching mechanisms, but one or two factors involved are worth noting.

Suppose a circuit is arranged as in Fig. 12.7, where W, a fine wire, is the collecting electrode, R a high resistance, and E the e.m.f. of the source used to create a potential difference between W and the wall of the chamber. With no ionization current, this p.d. is equal to E volts. But if the ionization current following the entrance of a particle suddenly rises to I amperes, then this p.d. drops to $E - IR$. Hence, the strength of the electric field in the chamber quickly drops to a value, which, by proper choice of R and by suitable design of the chamber, is not great enough to maintain a discharge. Moreover, because negative electrons move much more rapidly than the heavy positive ions, during the period the ionization current exists, there is a rapid removal of electrons to the wire W, accompanied by a comparatively slow movement of positive ions towards the wall. This slow movement of positive ions gives rise to a positive space charge whose presence still further weakens the field near the wire W and assists quenching. Quenching is also assisted by the use of suitable gases in the chamber. For example, the halogens chlorine and bromine have quenching properties and counters have been made using neon with the addition of small amounts of these gases.

The beginner, however, need not be concerned greatly about quenching mechanisms, if he has grasped the essential ideas that the entrance of a single ionizing particle into a counter chamber can be observed and recorded, and that the corresponding ionization current in the chamber can be quenched so rapidly that the entrance of many particles every second can be counted.

By recording photographically on a moving film the movements of the fibre of a string electrometer, the entry of several hundred particles per minute can be recorded. Modern counters, however, make use of different types of vacuum tube circuits, some of which can record mechanically pulses as rapid as 3,000 per second. For recording rapid pulses mechanically, so-called "scaling circuits" are used in connection with the counter. For example, the "scale of

two " in common use, employs electronic devices designed so that a register is made for every 2 particles entering the chamber, or every 4, 8, 16, etc.

Proportional Counter. Depending on the applied voltage between the central wire and the wall of the chamber, counters are used in two main ways : (i) in the proportional region ; (ii) in the Geiger region. A proportional counter is used with such a range of voltages that the flow of charge to the central electrode following the cumulative ionization, although many times greater than the initial number of ions created by the original ionizing particle *is always proportional to this initial number.* With such a counter, therefore, one can readily distinguish between the entrance into the chamber of a high speed electron or a beta ray and an alpha particle because of the much smaller number of ions created by the electron than by the alpha particle. The observed signal caused by the entrance of an electron will consequently be much less intense than in the case of the alpha particle.

Geiger-Mueller Counter. Beyond the range of voltage suitable for a proportional counter, there is a region of still higher potential differences such that the flow of charge to the central wire following cumulative ionization is independent of the number of ions created by the original ionizing particle, being just as great for a beta ray as for an alpha particle. A counter designed for operation in this region is called a Geiger-Mueller, or sometimes simply a Geiger counter. In a properly designed counter of this type, there is a considerable range of voltages (the plateau region) such that the number of counts per minute recorded by the counting mechanism is independent of the actual value of the voltage, a necessary condition if the number of counts per minute is to equal the original number of particles entering the chamber each minute.

Geiger-Mueller counters can be used for many purposes, their construction and design naturally varying somewhat with the use to which they are put. The importance of suitable potential differences has already been indicated. Two other important variables are the nature of the gas in the chamber and the gas pressure. With regard to these factors there is considerable leeway. Pure gases like hydrogen, helium, nitrogen, have been used, also mixtures like argon-hydrogen, neon-hydrogen, argon and alcohol vapour, and various polyatomic gases, such as methane. The total pressure of the gases in the chamber covers a wide range. Values have been recorded as low as 5 cm of mercury and as high as 60 cm.

Of the many varieties of counters reference is made to only a few. One especially designed for alpha particles is illustrated in Fig. 12.8, a diagram reproduced from the book *Electron and Nuclear*

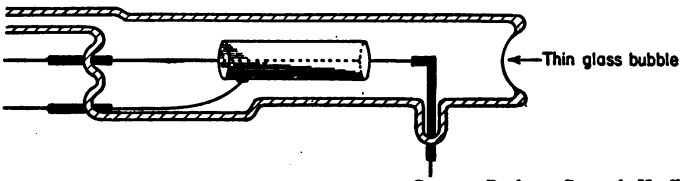


FIG. 12.8. Ionization chamber for a Geiger-Mueller counter suitable for alpha particles.

Counters, by Korff, by kind permission of the author and the publishers, D. Van Nostrand Company, Inc., New York. The glass window must be thin enough to permit the passage of alpha particles.

Of great importance to the radiologist is the fact that Geiger-Mueller counters can be used to detect and to measure X-rays and gamma radiation. This is possible because of the secondary electrons (photo or recoil) produced by these radiations. If a photon on entering a chamber causes the emission of a secondary electron, the electron can ionize along its path, and counter action is possible. Sometimes to increase the sensitivity of a counter for certain types of radiation, the wall of the chamber is coated with a material giving a marked photoelectric emission when struck by the radiation to be tested.

In another counter designed by Veale* for the examination of radioactive liquids, a thin-walled tube, whose surface is coated with graphite, acts as the cathode and is surrounded by an outer tube with thicker wall. The radioactive liquid is placed in the annular space 2 mm wide between the tubes. This counter, which may be used for both beta and gamma rays, contains a mixture of 90 per cent air and 10 per cent ethyl alcohol at a pressure of 10 cm.

A 4π counter is of special importance when it is desired to measure the absolute activity of a radioactive specimen, that is, to evaluate the actual number of disintegrations per second. As its name implies, it is so constructed that particles emitted in all directions by a small specimen placed at the centre of a spherical chamber are counted. For beta rays the efficiency of a 4π counter may be as high as 100 per cent. Efficiency of a counter, it should be added, is measured by the ratio of the number of pulses recorded to the total number of the

* Manufactured by Twentieth Century Electronics, Ltd.

original ionizing particles or photons. With the ordinary Geiger counter, for gamma rays it may be as low as 1 or 2 per cent. For that reason, as well as for others, the development of the scintillation counter described below, with its greatly increased sensitivity and efficiency, is one of the most important advances in radiological physics.

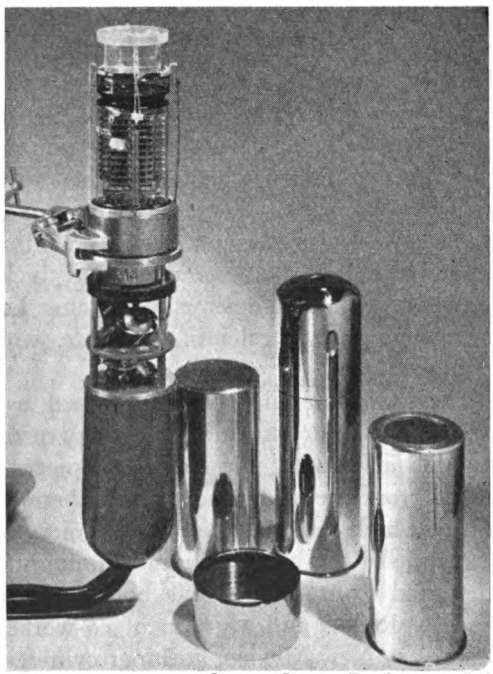
12.8. Photomultiplier Tube. The construction of a scintillation counter was made possible by the development of the *photomultiplier tube.* Its operation is based on two principles: (1) the photoelectric emission of electrons when visible light is incident on certain photosensitive surfaces (recall section 7.12); and (2) the emission of secondary electrons by certain surfaces when primary electrons impinge on them. In the photomultiplier, inside a highly evacuated tube there is a cathode—the *photocathode*—whose surface is coated with a photosensitive material, caesium treated with antimony, for example, on which light falls. The liberated electrons are then accelerated by an electric field and made to strike an electrode, sometimes called a *dynode*, whose surface* is so chosen that for *each* incident electron, 5 (or more) secondary electrons are emitted. The electrons liberated from this first dynode are then accelerated by an electric field† against a second similar dynode where the electron emission is again increased by a factor of 5 (or more). Since this process is repeated, 10 or more dynodes being used, the final emission, if we assume 10 dynodes and a multiplying factor of 5 at each, is 5^{10} or about 10^7 or ten million times the original emission at the photocathode. The current corresponding to this final emission is then lead off by a collecting electrode, to be still further amplified by standard electronic circuits. It should be obvious that *an extremely feeble source of light may be detected by a photomultiplier.* Some idea of the appearance of the tube may be had from the photograph of a scintillation counter reproduced in Fig. 12.9 through the courtesy of *Isotopes Developments, Ltd.*

In using the photomultiplier, background noise can create a serious difficulty, because, as will be evident from the above explanation, a single electron liberated from the photocathode by thermionic emission can give rise to considerable noise in the recording circuit. Thermionic emission and therefore the resulting noise can be reduced greatly by using liquid air to lower the temperature and in

* In one type of tube a caesium treated silver oxide surface is used, in another an activated silver-magnesium surface.

† In one type of tube, a potential difference of 100 volts exists between two successive dynodes.

some instruments this method has been used. Fortunately it can be lessened also, by a suitable choice of cathode material and by using a small surface area, sufficiently to permit the photomultiplier to be used in scintillation counters at room temperatures.



Courtesy Isotopes Developments, Ltd

FIG. 12.9. An exploded view of an I.D.L. scintillation counter head, type 653.

12.9. Scintillation Counter. In the *scintillation counter* a photomultiplier tube is combined with a *luminophor* that is, a substance in which flashes of luminescent light may result when it is struck by alpha, beta, or gamma rays. If a photon from a feeble gamma ray source strikes a luminophor and is absorbed, there is a resulting flash of light whose luminous intensity is, to a first order, directly proportional to the energy of the absorbed photon. If now a photomultiplier is placed with its photocathode near the luminophor, the light from each flash falls on the photosensitive surface (all other light being excluded), and electrons are liberated. As we have seen, their number is multiplied in the tube by a large factor and eventually by means of electronic circuits, a pulse is recorded in the measuring

device. In the ideal case each flash or scintillation gives rise to a single pulse.

With the scintillation counter gamma ray sources may be detected and measured with an efficiency much greater than with an ordinary Geiger-Mueller counter. For example, with a feeble source of cobalt^{60}, Belcher and Evans obtained 206 counts per second with a scintillation counter as against 35 per second with the G-M counter at the same distance from the source.

Suitable luminophor materials, which must be transparent to visible light and have a fairly high absorption for gamma rays, are few in number. In the counter to which reference was made in the previous paragraph, one which was designed for clinical use, the luminophor was a crystal of potassium iodide, containing $\frac{1}{2}$ per cent of thallium iodide, 10 mm in diameter and 7 mm thick. In another counter, designed for radiation dosimetry, Belcher has used single crystals of anthracene and of calcium tungstate, with dimensions about $3 \times 3 \times 3$ mm.

A liquid luminescent material may also be used, as in an instrument designed by Belcher for assaying the activity of small biological specimens. In this instrument the specimen, pieces of tissue, for example, removed from the body and treated chemically, is placed in a small test tube which dips into the liquid luminophor.

A striking example of the use of a liquid luminophor is found in instruments designed to examine whole body activity. In one of these, described by Reines and a group of co-workers at the Los Alamos Laboratory in New Mexico, an inner cylinder large enough to hold a good-sized dog or a small man in a crouched position, is surrounded by an annular layer of the luminophor. Beyond this there are 45 photomultiplier tubes joined in parallel. By means of this instrument, the amount of potassium 40 in the human body can be measured with good accuracy.

An important clinical application of the scintillation counter is found in external counting. Using crystals of small size, counters can be built with directional properties which are suitable for the examination of the activity of localized areas on the body. In this connection a brief reference is made to a special scanning instrument developed by Mayneord. In this instrument a narrow beam of gamma radiation emitted by a small portion of a radioactive source, after passing through a narrow aperture in a piece of heavy metal, falls on the crystal of a scintillation counter embedded in a block of lead. By a mechanical arrangement the heavy detecting system is

made to move in such a way that narrow beams from adjoining areas on the source successively pass through the aperture. This scanning process is repeated regularly for as long as is desired. In the original apparatus, the pulses from the counter were used to modulate the brightness of the cathode ray spot of an oscilloscope, mechanical gear making the spot scan the screen in synchronism with the movement of the detecting system. By this means a visual picture was obtained which showed the distribution of the radioactive material in the source under observation—for example, in the thyroid gland of a patient to whom iodine^{131} had been administered. In further developments of this instrument, the use of a storage tube made it possible " to see an image of the distribution of radioactive material as it is built up and the scanning proceeds even though that scanning takes minutes or even days ". (Mayneord.)

Reference to counters suitable for detecting and counting neutrons will be found in section 14.11.

12.10. Radium in Treatment. In therapy, radium is used in three important ways. (1) A small amount of a radium salt is enclosed in a tiny tube or needle, made of such metals as steel, monel, platinum, platinum-iridium, and gold. Although radium can be obtained in the metallic state, normally it is used as a salt in the chloride, bromide, or sulphate state. This needle, or a pack consisting of a group of several needles, is then used as a source of radiation. Usually the filtration is sufficient to restrict the rays to gamma only, but with thin walls some primary betas can emerge. As already noted secondary betas emerging from the metal container can be removed by additional filtration.

The amount of radium used in a single needle is of the order of a few milligrams. An applicator may be placed in contact with the tissue, or, if sufficiently powerful, at a few centimetres from it.

(2) In *radium beam therapy*, the source contains several grams of this radioactive element. In this case the patient, or more accurately, the tissue under treatment, is subjected to an intense beam of gamma rays. This is an example of *telecurie therapy* about which more will be said in discussing the uses of artificial radioactive isotopes.

(3) Needles or *seeds* of *radon* or *radium emanation*, a radioactive gas manufactured by radium, are frequently used instead of the original radium salt. Small glass tubes containing the radon may be embedded or *implanted* in the actual tissue under treatment, or they may be placed within metal containers like the needles mentioned above.

The difference between the use of radon and radium salt is explained below.

All the above methods, it will be noticed, deal essentially with gamma ray therapy. As already indicated, a certain amount of beta radiation is possible when a radium source is embedded in tissue. Since biological effects are almost certainly the result of ionization in tissue, and beta rays are ionizing agents, beta ray therapy cannot be over-looked. This is particularly true in connection with the use of the many artificial radioactive isotopes (discussed in Chapter XV) which can be injected into the human body, either as tracers or for possible selective absorption by specific organs.

12.11. Strength of a Radium Source. When radium needles are used, the dose delivered to the region treated depends on several factors: (1) the time of application; (2) the distance of the source from the diseased tissue; (3) the amount of absorption by the materials enclosing the radium salt and by tissue; and (4) the total quantity of radium sealed in the tube, that is, on what we may call the strength of the source.

The strength of the source is expressed in milligrams of radium, and it is measured by direct comparison with a standard. In 1912 a tube containing 16·74 milligrams of radium in the form of radium chloride, prepared by Madame Curie, was adopted as an international standard by a Committee of the Congress of Radiology and Electricity. This is kept in the International Bureau of Weights and Measures at Sèvre, near Paris. National secondary standards have been made by comparison with the international standard, and are in the possession of such institutions as the National Physical Laboratory in England, the Bureau of Standards in Washington, and the National Research Laboratories in Canada. When a radiologist buys a radium needle, its strength has been found by comparison with a National Standard and it should be accompanied by a certificate which reads like the following one.

This certifies that the above described needle has been compared with the standards of the National Research Laboratories, and found to emit gamma radiation equivalent to x milligrams of radium in equilibrium with its disintegration products and contained in a Thuringian glass tube 0·27 *mm thick.*

Note that comparison between the specimen and the National Standard is made by using gamma rays only. This is readily done by using an electroscope with a lead wall of sufficient thickness to absorb completely all beta rays falling on it. The specimen to be measured

and the standard are placed successively at the same distance from the electroscope, and in each case the rate of discharge measured. The two quantities of radium, as measured by gamma ray emission, are then in direct proportion to the rates of discharge, corrected in the usual way for natural leak.

The meaning of the phrase " in equilibrium with its disintegration products " is explained in sections 12.15 and 12.16.

Further reference to the measurement of the source strength of radium and other radioactive sources, will be found in section 12.19 and in later work on isotopes.

12.12. Dose in Roentgens. Measurements have shown that the quantity of gamma radiation received in 1 hour at a distance of 1 cm from a small source of radium element of strength 1 mg, enclosed in a platinum sheath 0·5 mm thick is 8·3 roentgens. This is sometimes called the *Sievert Unit*. If no correction is made for wall thickness, the number of 9 may be used to estimate the approximate dose. Stated otherwise, the above means that an *estimate* of the dose in *r* units, uncorrected for absorption or for finite size of needle or of number of needles in an applicator, may be made with fair accuracy, by the following relation.

$$\text{Dose} = \frac{9 \times \text{milligrams of radium} \times \text{time in hours}}{(\text{distance in centimetres})^2} \text{ roentgens.}$$

For example, for a 10 mg needle, used for 2 hours, the dose at 5 cm from the source is $\frac{9 \times 10 \times 2}{25}$ or 7·2 roentgens. If the needle is surrounded by 0·5 mm of gold, by using the coefficient 0·14 for gold given in Table XXIII, we see that this dose when corrected for absorption by the gold, is $(1 - 0{\cdot}5 \times 0{\cdot}14)$ or 93 per cent of 7·2.

For more accurate work, especially where a number of needles are combined in different arrangements to make applicators of different shapes, there are available dosage tables which a radiologist can consult.

Another unit of the strength of a gamma ray source is the rhm. As the letters suggest, one rhm is such a strength that the dose delivered in 1 hour at a distance of 1 metre in air is 1 roentgen.

The whole question of dosage in gamma ray therapy is discussed more extensively in section 15.11, under *k* factor.

12.13. Radon. Suppose a radium salt is heated and the occluded gases collected and sealed in a tube ; or, alternately that a solution of radium chloride in dilute hydrochloric acid, which has stood for some time is boiled and that the gases driven off are collected. It is found,

by testing with an electroscope, that the tube containing the gases is strongly radioactive. If measurements of the ionization are made every hour by a gamma-ray electroscope, it is noticed that at first the activity of the tube increases until, after some five hours, it has reached a maximum. Thereafter, if the tube is examined every 24 hours for a succession of days, it is found that its radioactivity steadily becomes less and less. The numbers given in Table XXIV show the rate at which the tube loses its radioactivity.

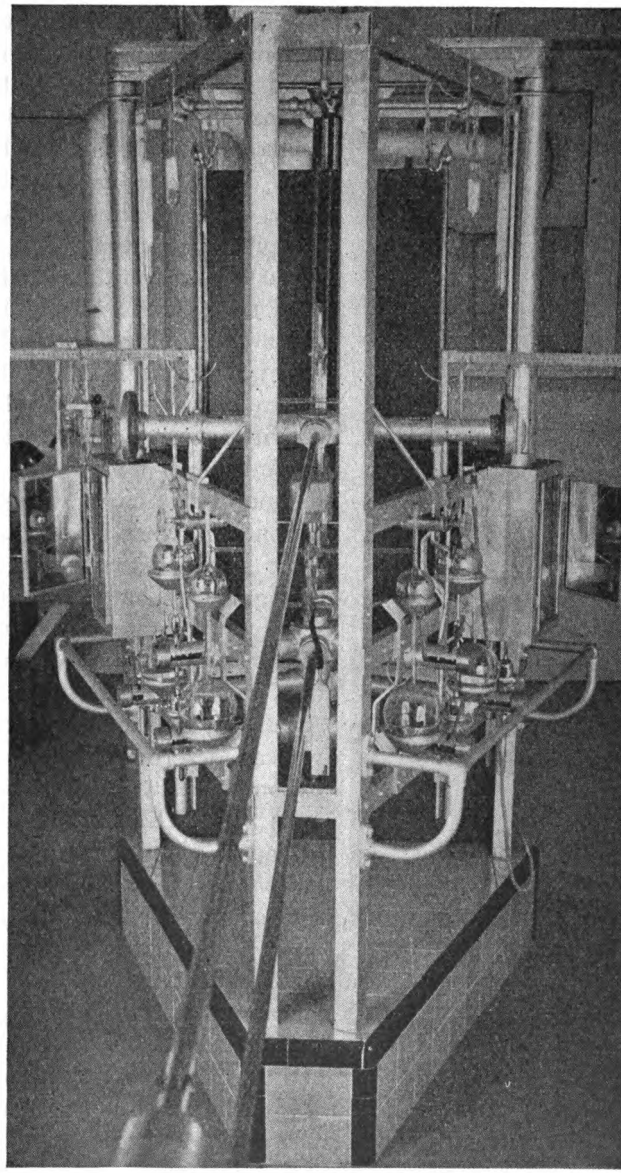
TABLE XXIV—DECAY OF ACTIVITY OF RADIUM EMANATION

Time	Activity	Logarithm of Activity	Change in Log per Day
0	100·0	2·000	·078
1 day	83·5	1·922	·079
2	69·7	1·843	·078
3	58·2	1·765	·078
4	48·6	1·687	·079
5	40·6	1·608	·078
6	33·9	1·530	·078
7	28·3	1·452	·079
8	23·6	1·373	·079
9	19·7	1·295	·077
10	16·5	1·218	—
20	2·7	—	—
30	0·45	—	—

It should be clear from this table that, although the gases collected from a radium salt or a radium solution, exhibit marked radioactivity, they differ in one important respect from the original radium preparation. When a needle containing a radium salt is tested day after day no change* is detected, but, with the tube containing the gases, the numbers in Table XXIV show that *its activity at the end of a month has almost disappeared.*

In addition to the radioactive constituent in the tube, the gases collected contain hydrogen, oxygen, helium, and carbon dioxide. When these are removed by appropriate means, what is left is a radioactive gas, called *radium emanation* or *radon.* From a gram of radium, only about three-fifths of a cubic millimetre at atmospheric pressure, can be obtained. Radon has been shown to be an element of atomic weight 222, belonging to the family of the rare gases. Chemically, there is nothing remarkable about it, but in radiology it is of tremendous importance. With a suitable emanation plant, it is

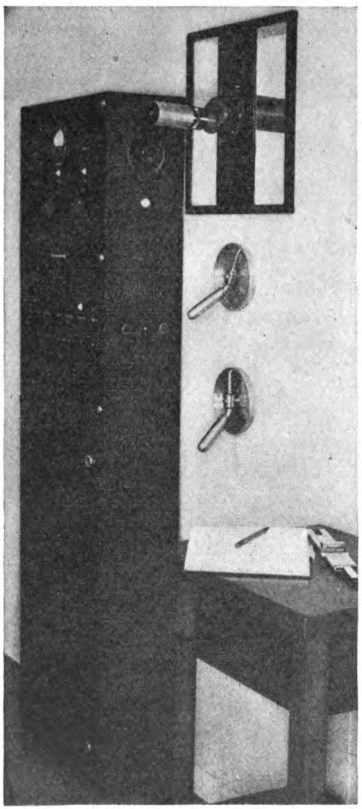
* More accurately, at the end of 1 year, a loss of 4 parts in 10,000 can be detected.



Courtesy G. Failla and Edith Quimby

FIG. 12.10. Semi-automatic control radon extraction apparatus, designed by G. Failla (Memorial Hospital, New York) and installed by J. E. Rose, United States Marine Hospital, Baltimore.

possible to keep a supply of radium, and without touching the original source, to seal the radon into glass tubes and use them instead of radium needles. Figures 12.10 and 12.11 are photographs of an emanation plant designed by G. Failla of the Memorial Hospital, New York, and installed by J. E. Rose, in the United States Marine Hospital, Baltimore.



Courtesy G. Failla and Edith Quimby

FIG. 12.11. Control panel for radon apparatus shown in Fig. 12.10. The control room and the radon apparatus are separated by a two-foot concrete wall.

To use a radon tube intelligently, it is necessary to be familiar with the law governing its loss of activity, that is, of what is called its *decay*. If we plot the results of Table XXIV, activity against time, we obtain the curve 1 shown in Fig. 12.12. Examination of this curve shows it to be exponential, that is, of exactly the same shape as that given in curve 1, Fig. 7.4. That figure, it will be recalled, illustrates the reduction in intensity of a homogeneous beam of X-rays as a result of absorption. As already indicated in section 7.10, we can describe in three ways an exponential law. In terms of curve 1, in Fig. 12.12, showing the decay of radon, we may state: (1) *Each day the activity decreases by* 16·5 *per cent of the activity of the preceding day*. Thus, if we decrease 83·5 by 16·5 per cent, we obtain 69·7. Or, if we decrease 69·7 by 16·5 per cent, we obtain 58·2. (2) In 3·82 days the activity has decreased one half. This time is the *half-period* of radon. (3) The curve is exponential and therefore is described by the law $I = I_0 e^{-\lambda t}$, where I_0 is the initial activity and λ is a coefficient called the *transformation* or *disintegration constant*. From this law it follows, as already shown in section 7.10 that the logarithm of the activity decreases by the same amount each day (or any time interval). This is shown by the numbers in the last column of Table XXIV.

If we use logarithms, the exponential law may be written

$$\lambda = \frac{2{\cdot}30\,(\log_{10} I_0 - \log_{10} I)}{t}.$$

For radon, this gives us

$$\lambda = \frac{2{\cdot}30 \times {\cdot}078}{1} = 0{\cdot}18 \text{ day}^{-1},$$

if the time is expressed in days.

It is left as a problem for the student to prove that T, the half-period, that is, the time in which the activity falls by one half (from I_0 to $\frac{1}{2}I_0$, for example) is connected with λ by the relation

$$T = \frac{0{\cdot}69}{\lambda}.$$

For $\lambda = 0{\cdot}18$ day^{-1} this gives 3·82 days for T.

Further information about the transformation constant and its relation to disintegration is given in section 12.17.

Problem: *By what percentage does radon decay in* (*a*) 3 *days*, (*b*) 100 *hours*? *Given half-period* = 3·82 *days.*

(*a*) As noted above,

$$\lambda t = 2{\cdot}30\,(\log I_0 - \log I)$$
$$= 2{\cdot}30 \log \frac{I_0}{I}.$$

But
$$\lambda = \frac{0{\cdot}69}{T}$$
$$= \frac{0{\cdot}69}{3{\cdot}82} \text{ (day)}^{-1}$$

and $t = 3$ days,

therefore $\lambda t = 0{\cdot}542.$

Substituting in above relation, we find

$$\frac{I}{I_0} = 0{\cdot}58,$$

or percentage decay = 58 per cent.

(*b*) Here it is more convenient to express the time in hours, in which case

$$\lambda t = \frac{0{\cdot}69}{3{\cdot}82 \times 24} \times 100 = 0{\cdot}753.$$

Hence we find percentage decay = 47 per cent.

12.14. Average Life. The term *average life*, symbol τ, should not be confused with half-life or half-period, defined above. As its name implies, average life is the arithmetical mean of the lives of all the atoms in a given radioactive nuclide. A calculation involving calculus shows that

$$\text{average life} = \frac{1}{\lambda}$$
$$= 5{\cdot}52 \text{ for radon.}$$

It can be shown that $\frac{1}{\lambda}$ is the time required for the activity of a specimen to fall to $\frac{1}{e}$ or $\frac{1}{2{\cdot}72}$ of its initial activity, as against $\frac{1}{2}$ for the half-period. (See solution of problem 18 at end of this chapter.)

12.15. Growth of Radon. Suppose from a supply of radium chloride kept in solution, all the radon is collected at various time intervals. It is found that, when the solution has been left untouched for a month or two, the radioactivity of the collected radon at the end of such an interval is just as great as when the solution is left untouched for six months, or a year, or two years, or any long period. On the other hand, if the radon is collected after intervals of 1 day, 2 days, 3 days, and so on, the activity is found to be greater the longer the interval, until a maximum is reached after about one month. The numbers in Table XXV and curve 2 in Fig. 12.12, show the exact rate at which the activity increases, maximum activity being assigned the value 100.

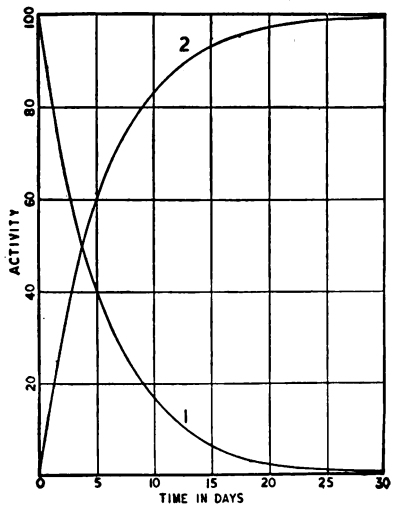


FIG. 12.12. Graph 1 shows the decay of radium emanation, graph 2 its growth.

The figures of Table XXV are readily interpreted in terms of two processes. (1) The manufacture or growth of radon *at a constant rate*, and (2) its decay in accordance with the law already explained, namely, that each day the loss of activity of radon is 16·5 per cent of its activity the preceding day. If we start with a quantity of radium salt initially free from radon, each day a certain amount of radon is

manufactured, and at first the total amount steadily increases. But, as the total quantity increases, the amount decaying also increases, until ultimately a balance is reached when the loss in a day due to decay is exactly equal to the amount added.

TABLE XXV—GROWTH OF RADIUM EMANATION FROM RADIUM

Time Interval	Percentage of Maximum Value
1 day	16·5
2	30·3
3	41·8
4	51·4
5	59·4
10	85·5
20	97·3
30	99·5

A financial illustration may not be amiss. Suppose a man deposits in a bank £16 10s. every day, and, in addition, each day (after the first) before he makes his deposit withdraws 16·5 per cent of the amount to his credit. His account will increase in exactly the same way as the figures of Table XXV, but it will never exceed £100. When that amount is reached, he takes out 16·5 per cent or £16 10s., and puts in exactly the same sum. Equilibrium has been obtained.

As Fig. 12.12 shows, the curve giving the growth of radon is complementary to the curve for decay. The law of growth therefore, for radium initially free from its emanation is written

$$I = I_0 (1 - e^{-\lambda t}),$$

where I_0 is the maximum activity when equilibrium has been established and I is the activity t seconds after the radon began to grow.

Sometimes radon when used clinically is left permanently in the tissue under treatment. A couple of months after a seed of radon of strength x mc* is implanted its activity for all practical purposes has dropped to zero. (See Table XXIV.) After such a time it is customary to say that x mc have been destroyed.

When a radium needle is used, since its decay is negligible during the time of any treatment, dosage is often expressed as so many milligram-hours. *A practical problem then is to find the number of mg-hours equivalent to* 1 *mc of radon destroyed.* Let us deal with 1 mc.

In section 12.14 we have seen that the average life of all the atoms in any sample of radon is equal to 5·52 days, or 132 hours. This

*For meaning of mc see section 12.16.

means that the sum total of the radiations emitted by a given amount of radon when it is allowed to decay until its activity has dropped to zero is the same as if it continued to emit its radiations *at an unchanged rate* for 5·52 days or 132 hours. Since 1 mc of radon initially is equivalent to 1 mg of radium, it follows that

dose when 1 *mc is destroyed* = 132 *mg-hrs.*

This is an extremely useful relation whose application is illustrated by the following problem.

Problem: *A certain treatment requiring* 25 *mg of radium for* 100 *hours has to be carried out by the use of radon seeds. Find the number of mc of radon required*: (*a*) *if the seeds are left permanently in the tissue treated*; (*b*) *if the seeds are left for* 100 *hours.*

(*a*) Dose = 2,500 mg-hrs.

But 1 mc destroyed = 132 mg-hrs.

Therefore required number of mc $= \frac{2{,}500}{132} = 18{\cdot}9$ mc.

(*b*) As worked out in the problem solved in section 12.13, the percentage decay of radon in 100 hours = 47·2 per cent.

Hence, 52·8 per cent is *destroyed* in that time.

Therefore, if number of millicuries required initially is x mc, the number destroyed during 100 hours = $0{\cdot}528\,x$.

Therefore dose = $0{\cdot}528 \times 132$ mg-hrs.

But dose = 2,500 mg-hrs.

Hence $x = \frac{2{,}500}{0{\cdot}528 \times 132} = 36$ mc.

Further work relating to dosage when other short lived isotopes are used is given in Chapter XV.

12.16. The Curie and Millicurie—Original Meaning. As we have seen above, when radon accumulates in a vessel containing a radium salt, a fixed maximum balance or *equilibrium* amount is reached in a little over a month's time. If the quantity of radium is 1 gram, the equilibrium amount of radon is called 1 *curie*; or if 1 milligram of radium is available, the equilibrium amount is 1 millicurie (mc). In actual practice, provided the original quantity of radium is sufficient, it is not necessary to wait until equilibrium has been established. From the numbers given in Table XXV, it should be evident that from a 100 mg supply of radium, every day a tube containing 16·5 mc could be obtained. From a 1,000 mg source 165 mc of radon are available every day. This can be subdivided

among a number of tubes or seeds. For example, sixteen tubes each containing about 10 mc can be supplied every day by a centre possessing 1 gram of radium and an emanation plant.

The use of radon tubes has the great advantage that the original radium supply is left untouched, with no danger of the loss which sometimes occurs when radium needles are used. Moreover, from a single centre tubes with an initial activity of the same order as that of small radium needles can be sent all over the country. On the other hand, in reckoning dosage, radon seeds have the disadvantage that correction must be made for the decay in activity. That, however, involves only a little arithmetic.

Although *as far as radium is concerned* the above definition of the curie is correct, it has now a much more general meaning and is widely used as a unit for the measurement of the strength of all radioactive sources. Its more general meaning is explained in section 12.19.

12.17. Disintegration and Nature's Transmutation. If radium emanation disappears, and this seems to be the case, since it steadily loses its radioactivity, what becomes of it? As always, experiment helps provide the answer. When a metal wire, preferably negatively charged, is inserted in a tube containing radon, left for two or three hours, and then removed, it is found to be radioactive. Careful investigation shows that the wire is coated with an invisible layer of solid material to which the name *active deposit* is given. If the coated wire is tested by an electroscope at successive time intervals of about 10 minutes, it is observed that the activity steadily decreases.

Now what is the explanation of these changes? The story of the unraveling of these somewhat mysterious radioactive processes, one of the most fascinating in the history of physics, was first given by Rutherford working in collaboration with Soddy, about the beginning of this century. To understand it, the student is first asked to recall that an alpha particle has a mass of 4 on the atomic weight scale and a charge of 2 positive units. It is, therefore, an ionized atom of atomic weight 4 and atomic number 2, and these numbers strongly suggest the element helium. Evidence that an alpha particle is indeed a doubly ionized helium atom was found in the early days of the study of radioactivity. Helium was found occluded in radioactive ores, and in 1903 Ramsay and Soddy showed that it was present in radium emanation. But most striking of all was a direct experimental proof made in 1909 by Rutherford and Royds. Alpha rays from a radioactive source enclosed in a vessel were allowed to escape through an extremely thin

glass window into a second vessel, where they were collected. By a spectrum test it was shown that helium was present in the second vessel in an amount which gradually increased with the number of alpha particles collected. This proved conclusively that alpha particles were nothing but the nuclei of helium atoms.

We may conclude, then, that the element radium shoots off atoms of helium. In considering where they come from, it is well to recall that the difference between the atomic weight of radium, 226, and that of radon, 222, is 4. The conclusion that the alpha particle is ejected right out of the nucleus of a radium atom can scarcely be avoided. It is an example of the disintegration of an element which occurs spontaneously with radioactive materials, and it is this property which distinguishes a radioactive element from a nonradioactive one. The nuclei of the atoms of radioactive elements are unstable, those of ordinary elements stable. (In Chapter XV, we shall see that it is possible to *create* unstable isotopes for many elements whose *normal* isotopes are stable.) Due to this instability, every now and then an explosion occurs, and a particle is ejected from the nucleus, leaving behind the nucleus of a new atom. This process, therefore, is a genuine example of the transmutation of one element into another. Radium, a metal belonging to the barium family, is

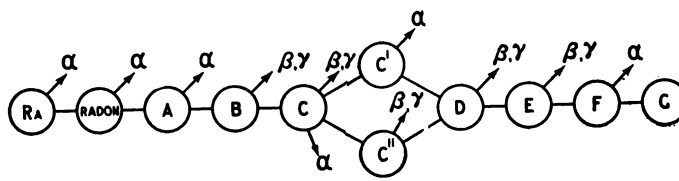


FIG. 12.13. Schematic representation of transformations from radium to radium G or lead.

transformed by the ejection of alpha particles, into radon, a member of the rare gas group. Since the atomic number of radium is 88 and the alpha particle has an atomic number of 2, the atomic number of radon must be 86.

This transformation or transmutation from radium to radon is but one step in a whole series of successive changes, all of which have been carefully investigated. Atoms of radon are unstable, and when they explode, they also shoot off alpha particles leaving behind atoms of radium A. This is another radioactive substance, with a half-period of three minutes. The process of disintegaration continues and radium A, emitting alpha particles, is followed by a series of successive generations—radium B which changes to radium C by

the emission of beta and gamma rays; radium C to C′ by the emission of beta and gamma, and C′ to D by the emission of alpha (or alternately C to C″ by the emission of alpha and C″ to D by emission of beta and gamma); D to E by the emission of beta and gamma; E to F by emission of beta and gamma; and finally F (polonium) to G by the emission of alpha. There the process stops because radium G is stable, being nothing but common lead.

This series of transformations is visualized by the diagrams of Fig. 12.13, and further details about half-periods are given in Table XXVI.

In connection with Table XXVI, the following things should be noted.

(1) The half-period of radium, 1,600 years, is so long that the total loss, even in the course of a year, may be neglected.* For that reason, the number of atoms of radon manufactured each day by a given amount of radium is, for all practical purposes, constant.

(2) Because of the long half-period of radium D, namely 22 years, it grows very slowly and hence, in a freshly prepared radium salt or tube of radon, the amounts of this product and of its posterity are extremely small. The active deposit is a mixture of the products A, B, and C.

TABLE XXVI—RADIUM AND ITS PRODUCTS

Substance	Atomic Weight	Atomic Number	Half-period	Emission
Radium	226	88	1600 years	alpha
Radon	222	86	3·82 days	alpha
Radium A	218	84	3·0 mins.	alpha
Radium B	214	82	26·8 mins.	beta, gamma
Radium C	214	83	19·7 mins.	beta, gamma
Radium C′†	214	84	2×10^{-4} sec.	alpha
Radium D	210	82	22·2 years	beta, gamma
or				
Radium C	214	83	19·7 mins.	alpha
Radium C″†	210	81	1·32 mins.	beta, gamma
Radium D	210	82	22·2 years	beta, gamma
Radium E	210	83	5 days	beta, gamma
Radium F (polonium)	210	84	139·5 days	alpha
Radium G (lead)	206	82	stable	

* In two months, the actual loss is about 0·007 per cent.

† It will be noted that radium C can disintegrate by two different processes to form, after two generations, radium D. Of all the atoms of radium C which disintegrate 99·96 per cent give birth to radium C′ and only 0·04 per cent to radium C″.

(3) It will be noted that radium itself gives off alpha rays only, although at the beginning of this chapter it has been stated that a radium salt gives off alpha, beta, and gamma rays. There is no real contradiction, however, because if a radium salt is sealed in a tube, disintegration is going on constantly and there is present in the tube a mixture of all the products. From the information given in Table XXVI, it will be seen that gamma rays are emitted by the products B and C. The emission from B is so weak and so feebly penetrating that for all practical purposes, radium C is the source of the gamma rays used in therapy.

We have stated above that, when radon is removed from a radium solution, maximum (gamma ray) activity is not reached for some five hours. This is because it takes that length of time before the maximum amounts of radium B and C are obtained.

(4) The end product, radium G, is stable, being in fact nothing but ordinary lead. In this connection, by means of a little elementary arithmetic, we can make a simple quantitative test. During the successive changes which take place in the transformation from radium to sterile lead, a total of five alpha particles and four beta are emitted. As far as the alpha particles are concerned, this represents a reduction in mass of 5×4 or 20 units. Since the mass of a beta particle is so small, we can neglect any change in mass due to it, except for very special calculations. Therefore, since the atomic weight of radium is 226, the atomic weight of lead should be $226 - 20$ or 206. Mass spectrograph data show that lead has an isotope of mass 206 in perfect agreement with this calculated value. But long before mass spectrograph data were obtained, Hönigschmid in Vienna in 1914 measured chemically the atomic weight of lead *obtained from pitchblende* and the value he obtained was 206·05.*

By the use of atomic *numbers*, another numerical test may be applied to radioactive transformations. Since an alpha particle has a charge of 2 positive units, a loss of 5 particles means a reduction in the total positive charge of 10 units. A beta particle, however, has a unit negative charge, and hence the loss of 4 beta rays means a decrease in total *negative* charge of 4 units or a *gain* of 4 positive units. The net result, therefore, of the loss of 5 alpha and 4 beta particles is a loss of $10 - 4$ or 6 positive units. Since the atomic number of radium is 88, it follows that the atomic number of lead should be $88 - 6$ or 82, as in fact it is.

* The student will recall that the ordinary (chemical) atomic weight for lead is 207·2. This is because it is a mixture of several isotopes.

(5) A glance at Table XXVI shows that radium B, radium D, and radium G or lead have the same atomic number 82. Chemically, therefore, these substances have the same properties, since the outer electronic system in an atom of each must be the same. Their atomic weights, however, are 214, 210, and 206. They are, therefore, radioactive isotopes of one and the same element. As a matter of fact, we owe the name isotopes to Soddy, the co-worker of Rutherford in the pioneer work on disintegration, because it was this work which first revealed their existence.

12.18. Meaning of Transformation Constant. It will now be seen that the term activity used in section 12.13 refers to the number of disintegrations per second. Hence we may re-write the relation $I=I_0e^{-\lambda t}$ as $n=n_0e^{-\lambda t}$, where n_0 is the number of disintegrations per second at a given instant and n the number per second after t seconds. It may be shown that we may write also

$$N=N_0e^{-\lambda t}, \tag{1}$$

where N_0 is the total number of the atoms in the nuclide at any instant and N is the total number existing after a time t.

It follows from relation (1), by an argument similar to that used in sections 10.12 and 12.5 in connection with the meaning of μ the linear absorption coefficient, that λ *the disintegration constant is the fraction of the total number of atoms breaking up each second.** Hence we can write

$$\textit{number of disintegrations per second}=\lambda N. \tag{2}$$

12.19. Equilibrium and Exact Meaning of Curie. True equilibrium exists between a parent radioactive substance A and its offspring B when, as is almost the case between radium and radon, the decay of B is exactly equal to its production by A. When equilibrium exists, if N_A and N_B represent the number of atoms in A and B, and λ_A and λ_B are the two disintegration constants,

$$\lambda_AN_A=\lambda_BN_B.$$

If a series of succesive products A, B, C, D, are in equilibrium, it follows that

$$\lambda_AN_A=\lambda_BN_B=\lambda_CN_C=\lambda_DN_D=\ldots$$

Two things immediately follow.

(*a*) The relative equilibrium amounts of any two products are inversely proportional to their decay constants or directly proportional to their half-periods.

* In section 12.13, λ for radon was given the value 0·18 because the time was expressed in days. More fundamentally λ for radon $=2{\cdot}1\times10^{-6}$ sec^{-1}.

(*b*) When equilibrium has been attained, *the number of atoms which disintegrate per second is the same for all products.* Hence the number of disintegrating atoms is an important number which can be used to describe the strength of a source.

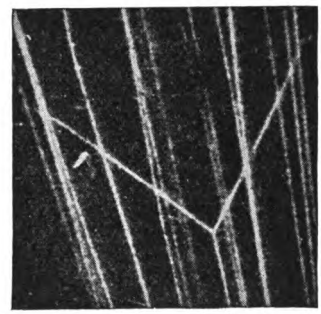
For that reason, the curie, although the definition given in section 12.16 is still correct *as far as radon is concerned*, has now a much more general meaning. Experimentally it has been found that the number of disintegrations per second per gram of radium is $3{\cdot}7 \times 10^{10}$ and hence also the number per second of 1 curie of radon. In consequence, *the curie has been chosen as a general unit of source strength, and is defined internationally as " the quantity of any radioactive nuclide in which the number of disintegrations per second is* $3{\cdot}700 \times 10^{10}$ *"*. The way in which the curie enters into the question of dosage when radioactive isotopes are used is discussed in section 15.11.

12.20. Secular and Transient Equilibrium. In the manufacture of radon from radium, the rate of production remains sensibly constant, decreasing, as we have seen, by an extremely small percentage in the course of a year. Hence, if a freshly prepared radium salt is set aside in a container, a radium needle for example, a close approximation to true equilibrium is obtained in about two months. The relative amounts of radium and radon remain constant. This is an example of *secular equilibrium.*

The situation is different, however, if the parent product decays rapidly. In that case it can be shown that, if a sample of A is taken initially free from its product B, and B is allowed to grow, in a short time the amount of B reaches a maximum at which for a moment $N_A\lambda_A = N_B\lambda_B$ and so true equilibrium exists. But, after this moment the amounts of both A and B decay with the same period, that of A. The two products are then in what is called *transient equilibrium.*

12.21. Artificial Transmutation. The whole story of disintegration shows that nuclei of radioactive atoms are complex and unstable and strongly suggests the complexity of stable atoms. If this is true, it is possible that a direct hit by a heavy particle like an alpha ray might smash the nucleus of an atom into its constituents. Breaking up the atom in this way must not be confused with releasing some of the electrons surrounding the nucleus. The removal of one or more of these extranuclear electrons does not destroy the atom, for subsequently other electrons are attracted by the ion and the atom returns to its normal state. Breaking up the nucleus is a different matter. It means a complete destruction of the atom, and for two reasons it is a very difficult thing to do. In the first place, it requires an enormous

amount of energy, and in the second place, the nucleus must be hit " head-on ". In some cases an alpha particle moving at high speed has the necessary amount of energy, but the chance of it making a direct hit is extremely slight. As the nucleus occupies about as much space in an atom as a fly in a cathedral, the vast majority of bombarding alpha particles pass right through the atom leaving it intact, except for the occasional removal of an outside electron.

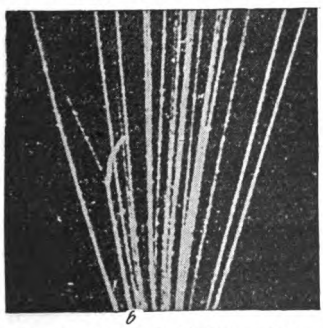


a

Courtesy N. Feather and the Royal Society

FIG. 12.14. Scattering collision of an alpha particle with the nucleus of a helium atom. The alpha ray, travelling along the path marked *a* strikes a helium nucleus and is deflected to travel along one arm of the fork, while the struck nucleus moves off along the other arm.

Sometimes the approach to the nucleus is so near that the alpha ray is deflected to one side, and, at the same time, the struck atom—or, more accurately, its nucleus—has energy communicated to it and moves off to the other side. Figure 12.14, a cloud-track photograph taken when alpha rays were bombarding ordinary helium, provides an excellent example of this. It will be noted that the tracks are straight lines for all but one of the particles. As the photograph clearly shows, the single exception is marked by a forked track, one prong of which corresponds to the deflected path of the original alpha ray, the other to the path of the struck helium nucleus.



b

Courtesy P. M. S. Blackett and the Royal Society

FIG. 12.15. Disintegration collision of an alpha particle with a nitrogen atom. The alpha particle, travelling along the path marked *b*, collides with a nitrogen nucleus and is captured. A disintegration results, the left-hand, long, thin arm of the fork marking the path of an ejected proton, the right-hand short, fat arm, the path of an ejected oxygen atom.

Occasionally the bombarding particle strikes head-on, and the struck nucleus, if light as hydrogen, is shot ahead with high speed. In one of the early experiments, for example, alpha rays bombarded hydrogen, and the protons which had been hit in this way, were observed to cause scintillations on a screen placed far beyond the range of the original alpha particle.

And sometimes the alpha particle enters right into or coalesces with the

bombarded nucleus, forming a new unstable atom which disintegrates. A transmutation is then the result. In 1919 Rutherford bombarded the gas nitrogen with alpha rays and obtained hydrogen because of such a process. This is then an example of what we shall call artificial transmutation, to distinguish it from the spontaneous natural transmutation of radioactive materials. The amount of hydrogen manufactured was too small to be detected by chemical means, but the most rigid tests showed that the effect was none the less real. There was no doubt about it. Protons or hydrogen nuclei were knocked out of nitrogen nuclei. The process of obtaining hydrogen in this way was not very economical, for a million alpha particles had to be fired to give one direct hit, and so to form one atom of hydrogen. But it was not the quantity of hydrogen evolved that mattered, rather the fact that a direct proof had been given that protons existed in the nuclei of nitrogen atoms. Within a few years it was shown that protons could be knocked out of many other atoms as well, and the view that all nuclei are composed of electrons and protons became widely held. In the light of subsequent work, some of which will be given in Chapter XIV, this view had to be altered.

Later we shall show that when an alpha particle interacts with a nitrogen nucleus with the emission of a proton, an oxygen atom is also formed. A cloud-track photograph of this transformation, taken a number of years after Rutherford's classic experiment, is shown in Fig. 12.15. In this photograph note the fork at the end of one of the alpha ray tracks. The long, thin " streak " forming one arm of the fork, corresponds to the proton path, the much shorter and somewhat irregular second arm, to the track of the oxygen atom.

12.22. Other Radioactive Families. In Table XXVI we have listed the various members of the radium family. These, however, are by no means the only radioactive substances which occur in Nature. Radium itself is a descendant through several generations of uranium I, a radioactive element of atomic number 92, atomic weight 238, with a half-period somewhat less than 5×10^9 years. Uranium II, the 234 isotope, with half-period $2{\cdot}7 \times 10^5$ years, occurs in this same family. Both these isotopes of uranium emit alpha rays. The third isotope, the 235 variety, occurs in another family called the actinium series, and is also an alpha ray emitter with a half-period of 7×10^8 years. The half-periods of all three isotopes of uranium are so extremely long that for many purposes, this element may be considered stable.

A third family consists of thorium products.

One of the members of this family is mesothorium, a substance which with an atomic number of 88, is an isotope of radium. For that reason, if radium and mesothorium are present in the ore from which radium is extracted, it is not possible to separate them by ordinary chemical means, and sometimes radium salts contain mesothorium as an impurity. This is not desirable, because, although mesothorium emits gamma rays, its activity decreases about 10 per cent in a year, unlike radium which, as we have seen, remains sensibly constant.

PROBLEMS AND QUESTIONS

1. Explain the meaning of " millicurie of radium emanation ".

2. What radiations are given off from a tube of radium emanation enclosed in a tube of platinum 0·5 mm thick?

3. If at a certain time you were provided with 100 millicuries of radium emanation, how much would you have after 48 hours? *Ans.* 69·7 mc.

4. A radium emanation tube sent from New York to Kingston had a strength of 100 millicuries when it left New York. (i) What is its strength when used in Kingston for treatment 48 hours later? (ii) After what time will its strength be 50 millicuries? (iii) After what approximate time will a 10 milligram tube of radium salt fall to half-value? *Ans.* (i) 69·7 mc. (ii) 3·82-days. (iii) 1,600 years.

5. The same type of curve is obtained when the decrease in the activity of radon is plotted against time as when the decrease in the intensity of a homogeneous beam of X-rays is plotted against the thickness of an absorbing layer of matter. Indicate the general nature of this curve, explaining the law which defines it.

6. On a certain day a radium emanation tube causes the leaf of an electroscope to fall at the rate of 60 divisions per minute. How fast will the same tube (at the same place) cause the leaf to fall (i) after 24 hours, (ii) after 48 hours? *Ans.* (i) 50·1 div. per min. (ii) 41·8.

7. If all the radon is collected every second day from 1 gram of radium, find the strength in millicuries of the amount collected, on the day collection is made. *Ans.* 303 mc.

8. One-tenth gram of radium is left standing in solution for at least a month. The accumulated radium emanation is then drawn off each day for three successive days, and each day sealed in a single tube. Find the strength of the three tubes on the third day. *Ans.* 69·7 mc, 16·5 mc, 13·8 mc.

9. If a gram of radium was the total amount in an emanation plant, what is the maximum number of 20 millicurie tubes which could be obtained from this plant at one time? (ii) About how long would it be necessary to wait before collecting the emanation to obtain this maximum number? (iii) What would be the strength of one of the 20 mc tubes 24 hours after it was removed from the plant?

10. A radium emanation plant, with 1 gram of radium in solution, has all the active gas removed on a certain day. Work out how many millicuries

could be taken from the plant on the next removal which takes place after an interval of three days. *Ans.* 418 mc.

11. Radium D has an atomic number of 82 and an atomic weight of 210. On emitting beta and gamma rays it changes into radium E, which in its turn also emits beta and gamma rays, changing into polonium. Finally polonium emits alpha rays, changing into lead. Show that lead and radium D are isotopes and find, from the above data, the atomic weight of lead.

12. The atomic weight of radium is 226, and its atomic number is 88. If the final stable product after the successive transformations of radium is lead, of atomic weight 206 and atomic number 82, find the total number of (i) alpha particles emitted, (ii) beta particles, by the time a single radium atom has turned into an atom of lead.

13. A radioactive substance A of atomic number 92 changes into B of atomic number 84 after a series of successive transformations. If in the process a total of 7 alpha rays are emitted, find the total number of beta rays emitted.

14. Radon is drawn off regularly every second day from an emanation plant containing 500 mg of radium in solution. Find the maximum amount (in millicuries) of radon which the plant can distribute every second day.

15. A small tumour is treated for 50 hours with gamma rays by 20 mg of radium in a needle. If the tumour is an average distance of 3 cm from the needle, estimate the dose in roentgens, without correction for absorption. *Ans.* 1,000r.

16. If radon is collected every day in an emanation plant containing 2 grams of radium, what is the maximum number of millicuries obtained each day?

17. A radioactive material decays according to a simple exponential law. If in 1 minute its radioactivity decreased by 10 per cent, find its half-period by plotting a graph, or in any way you like. *Ans.* 6·5 mins.

18. Given that 1 gram of radium (at wt 226) emits $3{\cdot}7 \times 10^{10}$ alpha particles per second, calculate: (*a*) the transformation constant; (*b*) the half-life; and (*c*) the average life of radium. Avogadro's number $= 6{\cdot}06 \times 10^{23}$.

Solution

(*a*) Number of atoms in 1 gram of radium $= \dfrac{6{\cdot}06 \times 10^{23}}{226}$.

Therefore $\lambda \dfrac{6{\cdot}06 \times 10^{23}}{226} = 3{\cdot}7 \times 10^{10}$

or $\lambda = 1{\cdot}37 \times 10^{-11}\ \text{sec}^{-1}$

(*b*) Half-life $= \dfrac{0{\cdot}69}{\lambda}$ (from section 12.13)

$= 1{,}600$ years.

(*c*) Average life $= \dfrac{1}{\lambda}$

$= 2{,}320$ years.

19. Calculate the mass of 1 curie of radon, given that the half-periods of radium and of radon are 1,600 years and 3·82 days respectively, and that the atomic weights are 226 and 222. *Ans.* $6{\cdot}41 \times 10^{-6}$ gm.

20. A certain treatment requiring 25 mg of radium for 200 hours has to be carried out in the same overall time using radon. Calculate the number of millicuries required.

21. If the half-life of radon is 3·82 days, after what time will 0·875 mc be present in a tube containing 1 mg of radium initially free from radon? *Ans.* 11·5 days.

22. A mould to deliver 6,000*r* in 8 days continuous treatment was to have been loaded with 15 mc of radon. It was found that the radon was not available and must be replaced by radium. How much radium is required if the treatment is to be for 12 hours daily? (Assume half-life for radon = 4 days.)

23. Given that the mass of 1 curie of radon is 6·42 micrograms and that the half-period of radium (at wt 226) is 1,600 years, calculate to what strength a 10 mc source of radon will have decayed in 2 days.

CHAPTER XIII

PRODUCTION OF HIGH VOLTAGE. *Part II* SUPERVOLTAGE TUBES AND HIGH SPEED PARTICLES

13.1. Importance of Supervoltage. The construction of supervoltage machines has played an important part in the development of radiological and nuclear physics. In Chapter II only a passing reference was made to this work, because it was considered advisable to defer the discussion until the reasons for using supervoltages could be made clear. Let us now examine some of them.

(1) From the relation

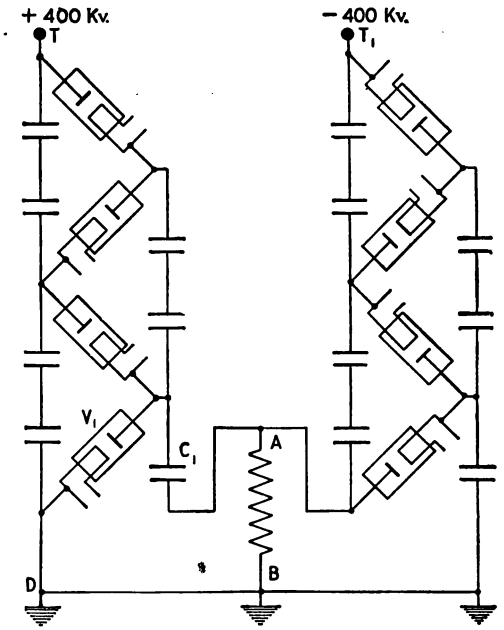
$$\text{shortest wave length} = \frac{12{\cdot}4 \times 10^3}{\text{maximum voltage}},$$

we see at once that the higher the voltage across a tube, the shorter the minimum wave length in the continuous X-ray spectrum. With a million volts, for example, the shortest wave length is about 0·012 angstrom. The wave length of maximum intensity in the continuous spectrum is, of course, somewhat longer than this.

Obviously, then, by using supervoltages, extremely penetrating beams of rays can be obtained and there is now a widespread use of such rays in radiology. Although as yet there is no marked evidence that they have any specific value in treatment, there are several advantages in using high energy radiation. (*a*) The more penetrating the rays, the higher the percentage depth dose delivered at a given place below the skin. (Recall section 11.16). (*b*) Because of the marked forward range of electrons liberated in tissue (or other media), the place where maximum energy is delivered is not at the surface, but below it. For example, with the 22 MeV rays generated by a betatron (section 13.9), according to data given by Johns, the region of maximum energy is some 5 cm below the surface. For the radiation from a cobalt^{60} unit (section 15.8) the maximum is at a distance of 5 or 6 mm. In this connection it should be noted that, for ultra-penetrating rays, it is customary to give dosage at a given depth in terms of 100 at the maximum rather than 100 at the surface. (*c*) It follows from (*b*) that undesirable skin reactions are much less

with these rays than with rays used in standard therapy. Moreover, Smithers, in emphasizing the small skin reaction with 2 MeV radiation in use at the Royal Marsden Hospital in London, adds that " the patient complained of no ill effects ", such as radiation sickness. (*d*) The abnormal absorption by bones of 200 KeV rays is absent with ultra-penetrating radiation. For example, again using data given by Johns, the energy absorption for 200 KeV rays is 91 ergs per gram per roentgen for tissue as against 300 ergs for bone, whereas, for 25 MeV rays, the figures are 92 ergs for muscle and 91 for bone.

(2) By means of supervoltages (or their equivalent) extremely high speed electrons, protons and a few other particles can be obtained. With such particles transmutation experiments can be carried out with results of great importance in radiology. There is also the possibility of using high speed electrons for biological and therapeutic purposes.



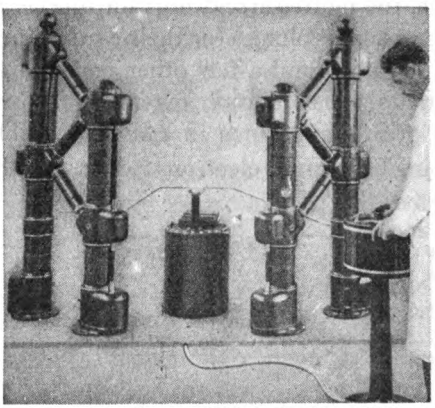
Courtesy Philips' Gloeilampenfabrieken

FIG. 13.1. The arrangement of rectifying valves and condensers in a cascade generator.

A number of different methods have been used for the development of supervoltages. Some of them are simple in principle, some are engineering jobs on a large scale. In the following sections we

shall examine briefly the main features of the more important methods.

13.2. The Cascade Generator. In this type, as developed by the Philips' Laboratories and the General Electric Corporation use is made of a combination of condenser and rectifying valve units similar to those used in the Villard and Greinacher rectifying circuits. (Sections 6.8 and 6.9.) An arrangement utilized in a Philips' generator of this sort, capable of developing 800,000 volts, is shown in the



Courtesy Philips' Gloeilampenfabrieken

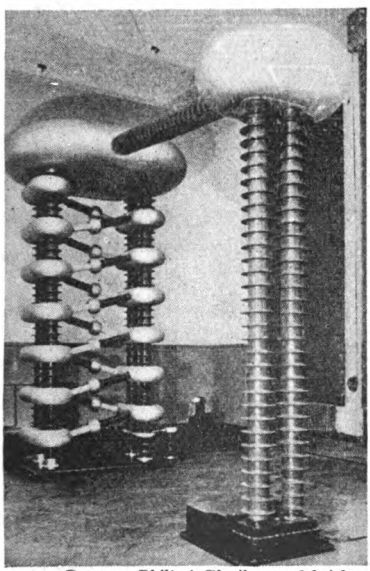
FIG. 13.2. Photograph of a cascade generator.

diagram of Fig. 13.1. In this figure it will be noted that the circuit BAC_1V_1D is similar to the Villard circuit of Fig. 6.16, except that only one rectifying valve and one condenser is used. By adding successive condenser-valve units in the manner shown in the figure, the original e.m.f. developed in the secondary AB of the high tension transformer may be so multiplied, that terminal T is raised to a high positive potential, T_1 to an equally high negative. In the generator represented in this figure, with a transformer voltage of only 100,000 volts T becomes $+400{,}000$ volts, T_1 $-400{,}000$ volts, hence between the terminals there is a p.d. of 800,000 volts. The photograph reproduced in Fig. 13.2 shows the actual appearance of this generator or one similar to it, whose total height is some 8 feet.

Making use of the same principle, the Philips' Company constructed a much larger generator for the Cavendish Laboratory, Cambridge, England. This machine, which has a total height of about 17 feet, develops 1,250,000 volts, although only 120,000 volts is necessary in the secondary of the transformer. Figure 13.3 shows the actual appearance of this generator. In this figure the generator

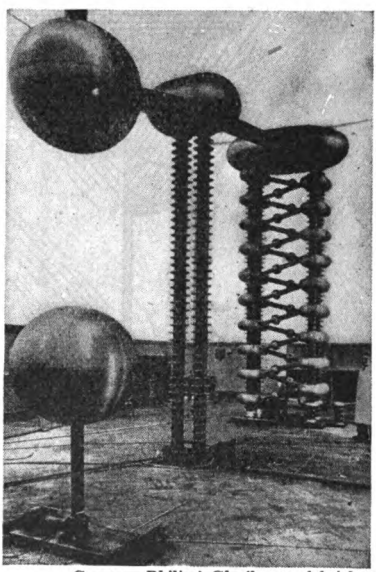
proper with its zig-zagging valves is seen on the left. The double column on the right contains an extremely high resistance which is used in the measurement of the actual voltage developed by the method described in sections 2.10 and 13.4. The horizontal piece at the top of the photograph is a damping resistance by means of which electrical connection is made to the top of the measuring resistance (as shown) and to the X-ray tube (not shown).

Figure 13.4 is a photograph of the negative end of a 4,000,000 volt generator used in the Philips' Laboratory at Eindhoven, Holland. An added feature in this photograph is the huge sphere gap, used for taking voltage measurements.



Courtesy Philips' Gloeilampenfabrieken

FIG. 13.3. A 1,250,000 volt cascade generator.



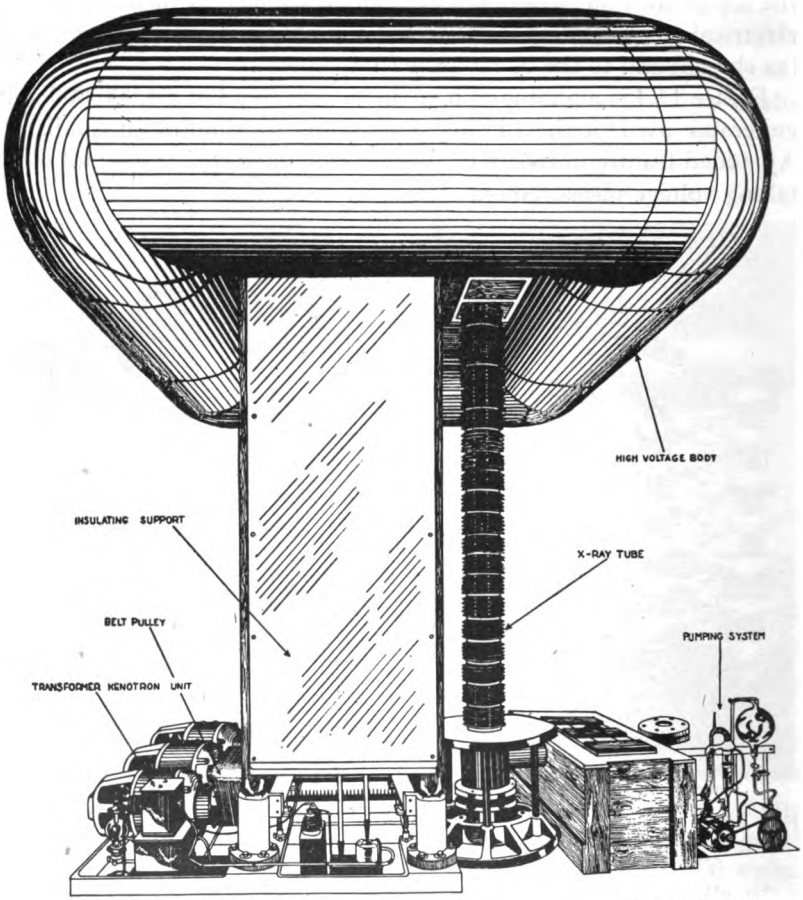
Courtesy Philips' Gloeilampenfabrieken

FIG. 13.4. The negative end of a 4,000,000 volt cascade generator.

In all supervoltage generators ample room must be left between the high tension terminals and the ceiling or other grounded places, otherwise " flashovers " will take place.

13.3. Van de Graff Generator. This type of generator, simpler in principle than the cascade type, cheaper to construct and stable in operation, is used to a considerable extent for developing potentials of the order of a few MV. The first machine of this kind was the invention of Van de Graaff, who made use of fundamental ideas discussed in elementary classes in electrostatics.

The student is asked to recall two of these. (1) An electric charge given to a hollow conductor goes to the outer surface, the potential at all points within such a conductor being the same. (2) An insulated charged conductor loses its charge if a pointed conductor is in contact

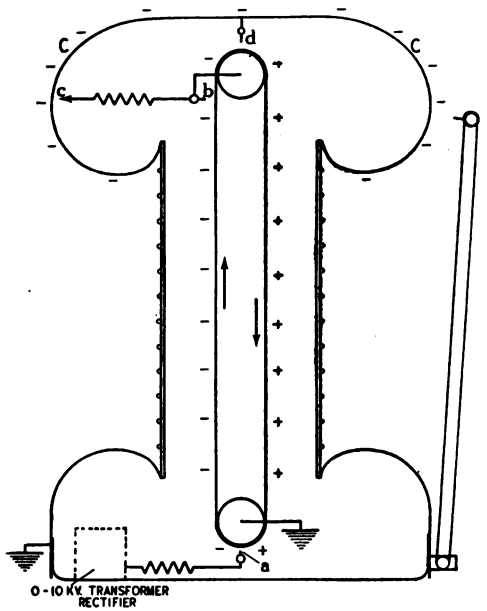


Courtesy J. G. Trump

FIG. 13.5. A Van de Graaff generator capable of developing 1,000,000 volts or more.

with it; or, conversely, an uncharged insulated conductor, with a sharp point attached to it, will pick off a charge from a charged body placed near the point. In the first case, we sometimes state that the charge " slips off " the point. Actually, the charge accumulates on the point to such an extent that the resulting electric field in the air

near the point is great enough to ionize the air. If the point is negatively charged, positive ions move towards it and annul its charge, thus leaving negative ions in the surrounding region. Similarly, before a point picks off a charge, there is ionization between it and the neighbouring charged body.



Adapted from illustration by J. G. Trump, F. H. Merrill and F. J. Safford

FIG. 13.6. Outline diagram of small Van de Graaff generator.

To understand the way in which these ideas are utilized in the Van de Graaff generator, a brief description is given of a comparatively small machine, designed by J. G. Trump and R. J. Van de Graaff, of the Massachusetts Institute of Technology. The general appearance of one generator of this kind, capable of developing a million volts or more, is shown in Fig. 13.5. The important details of the construction of a 500,000 volt generator may be understood by reference to Fig. 13.6. An electric charge is accumulated on a hollow, insulated conductor *C*, some thirty inches in diameter, and twelve inches high, which stands on the top of an insulating column over three feet long and twelve inches in diameter. The column rests on a supporting base in contact with ground.

Within the base, there is a small transformer-rectifier unit so arranged that a negative charge slips off a row of points, one of which

is represented by *a* in the diagram. These points are about one quarter inch from a *grounded* pulley revolved by a motor also housed within the base. A three-ply rubber fabric, making an endless belt about ten inches wide, passes around this pulley and a second *insulated* pulley, placed inside the insulated conductor at the top of the generator. When the machine is in operation, the motor keeps the belt moving at the rate of 5,000 ft. per minute. A collector rod with points at *b* and at *c* is attached to the upper insulated pulley.

The action of the generator is somewhat as follows. As the left-hand side of the belt goes up with its negative charge, negative electricity is picked off at *b*. Most of this slips off at *c* going to the outside of the terminal, but some goes to the insulated pulley. Since this is situated inside a hollow conductor normally its potential would be the same as that of the conductor, but when a free charge of the same kind is thus added to it, its (negative) potential becomes higher than that of the terminal conductor. Hence, when a row of pointed conductors is attached to the inside of the terminal, as represented at *d*, the higher negative potential of the pulley causes an escape of positive electricity from these points. This escape of positive: (1) still further increases the negative charge on the terminal; (2) annuls any negative left on the uprising belt; and (3) puts a positive charge on the downward belt. At the bottom of its downward path, the positive is annulled by the spraying action of the discharge points at *a*, and the process goes on until, in this particular instrument, the terminal attains a potential of 500,000 volts.

The value of the maximum attainable potential depends on the insulation and the shape of the upper terminal. In this connection it is worth while noting that an upper limit to the potential which any charged body may attain is reached when the electric field near any part of its surface has the value of about 25 to 30 kV per cm. When fields of this intensity are reached, ionization and corona discharge sets in. The smoothly rounded top of the generator is, of course, designed so that the highest voltage possible is attained before such a field strength is reached.

By the use of compressed air or the gas freon much higher voltages may be developed before any break down discharges occur, and more than one generator of the Van de Graaff type has made use of this fact. For example a generator has been built by Trump and Van de Graaff, capable of developing 1,250 kV. This is housed in a steel tank 100 in high, 34 in in diameter, containing air at a pressure of 11 atmospheres. Van de Graaff generators are now in general use both in

hospitals and in places like Harwell, where there are at least two, one with a rated maximum of 5 MV, a smaller one rated at 2 MV. An interesting clinical unit at the Royal Marsden Hospital, London, is housed, along with the X-ray tube, in a container capable of rotation and designed for use in connection with the rotating table to which reference was made in section 11.17.

13.4. Measurement of Supervoltages. In sections 2.5 to 2.10 some discussion was given of methods used in the measurement of high tension voltages. When potentials of the order of a million or more are used, naturally there are added difficulties, although the principles employed in most of the methods do not differ greatly from those already given.

(1) If the supervoltage is used to operate an X-ray tube, the maximum voltage applied to the tube can always be calculated from a measurement of the shortest wave length in the continuous spectrum. Reference has already been made to this method in sections 2.11 and 8.4.

(2) Values of supervoltages may be estimated with spark-gap meters, although calibration values are somewhat uncertain. The large size of spheres used, as large or larger than 100 cm in diameter, may be seen by a glance at Fig. 13.4. It is interesting to note that, in the High Voltage Engineering Laboratory at Pittsfield, Mass., spheres of spun aluminium, over 6 ft. in diameter permit direct measurements to be made up to three million volts.

(3) In section 2.10 reference was made to a method in which a high potential difference may be evaluated by placing an extremely high resistance in parallel with the unknown high voltage terminals, and then measuring the potential drop across a known fraction of the whole resistance. Attention has already been directed to Fig. 13.3, which shows on the right-hand side the external appearance of such a measuring resistance. This particular resistance, or one very similar to it, is made of 2,000 oil-immersed carbon units, each of 0·75 megohm, that is, with a total resistance of 1,500 million ohms. A high voltage of about a million and a half volts, then causes a current of about 1 ma through this resistance. By means of an electrostatic voltmeter, with a range up to 1,500 volts, the potential difference across 1/1,000 of the resistance is read directly off this instrument placed on the control panel of the machine.

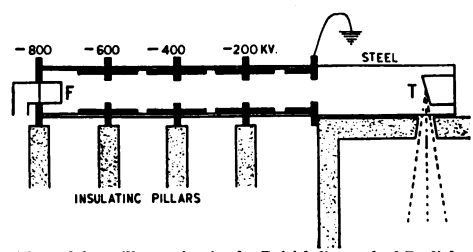
(4) *Generating Voltmeter.* An entirely different method has been used in an instrument called the generating voltmeter, described by Trump, Safford and Van de Graaff and used by them for voltages as

high as 1·5 MV. A description of this instrument, which is not in general use, is given in the second edition of this book.

13.5. Supervoltage Tubes. The problem of building tubes capable of operation on voltages of a million or more presents many difficulties. The insulation must be so good that there is no danger of spark-over on the outside of the tube itself. Care must be exercised to guard against a discharge in the tube even with a cold filament, because once an electric field reaches a certain value electrons can be pulled out of a cold metal. A good vacuum must be maintained in a tube, frequently of such large dimensions that vacuum pumps have to be in continuous use. Then, too, there are the added precautions necessary to protect both operator and patient from the dangers of electrical shock and from powerful beams of very penetrating rays.

Some of the different ways in which these and other difficulties have been overcome will be understood from the following brief description of a few representative supervoltage tubes.

The General Electric Company has constructed, along more or less standard lines, a sealed-off tube, some five feet long, which is capable of operation on 400,000 volts. In this tube, by placing the target near the inner end of a long hollow copper cylinder, electrons are pre-



Adapted from illustration in the British Journal of Radiology

FIG. 13.7. An 800,000 volt X-ray tube of the multisection type.

vented from bouncing off the target and charging the inner surface of the walls of the tube, one of the common causes of tube puncture. The envelope itself, one quarter of an inch thick, is made of borosilicate glass, a material with high dielectric strength.

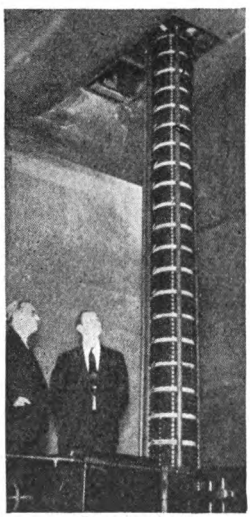
For much higher voltages, this firm has constructed multisection tubes, that is, tubes consisting of a number of glass cylinders separated by metal rings. Since the metal used is an alloy with the same coefficient of expansion as the glass, vacuum tight seals can be made. The metal rings are attached to electrodes extending inside the tube. By the use of these intermediate electrodes the total voltage between the

filament and the target is subdivided, and, " the metal cylinders exert a focussing action on the electron beam and protect the glass from bombardment . . . " (Read).

Fig. 13.7, adapted from an illustration in an article by J. Read in the *British Journal of Radiology*, represents a large 800,000 volt tube of the multisection type built by the General Electric Company for the Swedish Hospital, Seattle. It will be noticed that the voltage across each section is only 200,000, and that the target is at ground potential. The whole tube lies outside the treatment room which is heavily insulated against penetrating rays except for the window through which they pass to the patient.

Another General Electric tube of the multisection type consists of ten sections, is 28 ft. 6 in. long, and is able to carry 10 ma at 1,400,000 volts.

In most of the supervoltage tubes, the necessary low pressure has to be maintained by the continuous operation of exhaust pumps. The Philips' Company, however, have utilized successfully the multisection principle in the construction of sealed-off tubes capable of withstanding supervoltages. In the Philips' tubes, each unit has glass ends of the reentrant type, somewhat as used in the ordinary metalix tube, Fig. 5.16, and the units are connected by soldering external metal pieces at adjacent ends after each unit has been separately evacuated. Connection between the units is subsequently made by the electron beam itself, which perforates thin pieces of metal foil covering the central parts of the metal electrodes. A two-unit tube of this type has been constructed capable of operation on 700,000 volts ; and a three-unit tube, $6\frac{1}{2}$ feet long, is capable of continuous operation with 1 or 2 ma, at 1,000,000 volts.

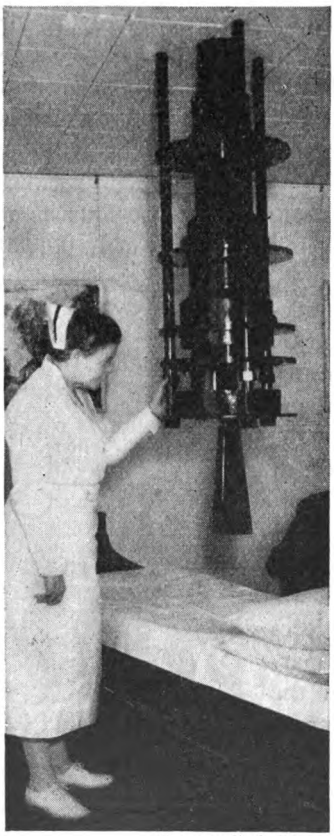


Courtesy J. G. Trump

FIG. 13.8. The million volt X-ray tube in the Huntington Memorial Hospital of the Harvard Medical School.

A million volt tube of an entirely different construction, developed at the Massachusetts Institute of Technology in connection with an electrostatic generator, is in use at the Huntington Memorial Hospital of the Harvard Medical School. The general appearance of this tube is shown in Fig. 13.8. (See also Fig. 13.5.) Insulation is provided by using a ten foot column of twenty porcelain sections resting

on a grounded steel flange at floor level. Below the flange, a steel cylinder, which forms the lower end of the X-ray tube, continues into the treatment room, as shown in Fig. 13.9. Electrons from a filament at the top of the tube are guided down the tube by electrostatic lenses, placed between each porcelain sector, until they strike the water-cooled lead target sixteen feet below. " The target consists of a copper cup on the inside of which a 15-mil lead coating has been electroplated, the cup being cooled by a water jacket. The target is at ground potential but insulated from the tube extension, so that the current to the target can be read on a milliammeter at the control panel. The X-rays utilized in treatment are those transmitted downward through the target and water-cooling jacket." (Trump and Van de Graaff.)



Courtesy J. G. Trump

FIG. 13.9. The lower end of the million volt X-ray tube shown in Fig. 13.8.

By way of contrast to this tube, a brief reference is made to one made by Metropolitan Vickers for use in the Mozelle Sasson High Voltage X-ray Therapy Department, at St. Bartholomew's Hospital, London. This tube, thirty feet long and weighing ten tons, extends horizontally through three rooms. In the first room a generator can maintain the cathode at a negative potential of 500,000 volts or more. The central part of the tube, a grounded steel cylinder containing the water-cooled gold target, lies in the middle of treatment room. Since in the third room, a second generator can maintain the anode at a positive potential of 500,000 volts, potentials of at least 1,000,000 can be applied to the tube. The anode and cathode ends are separated from the middle portion by porcelain insulators, each five feet long, and elaborate precautions are taken to provide adequate protection from the rays. In this connection we quote from a booklet describing this installation. " The position within the treatment room,

that is, the central twelve feet, is surrounded by a protective sheath, consisting of a six-inch layer of close-packed lead shot, enclosed between two coaxial steel cylinders. An aperture in this sheath allows the transmission of the X-ray beam. The protective sheath in its turn is surrounded by a steel cylinder which carries the filters, diaphragms, and applicators for defining the X-ray beam. The protective sheath and applicator cylinder can be rotated independently of each other. In this way it is possible to direct the beam of X-rays at will, either through the applicator towards the patient, or into an absorbing lead saddle, six inches thick, suspended immediately above the tube. Thus, the portion of the X-ray tube within the treatment room is both shock-proof and ray-proof."

13.6. High Speed Particles. For convenience we may divide instruments for accelerating particles until they have high energy into three classes.

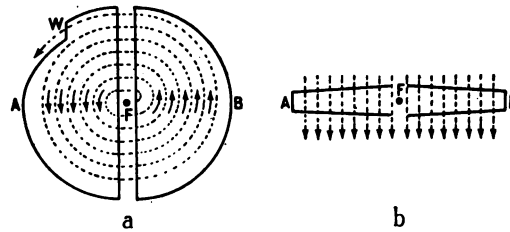
(*a*) Those in which a high voltage is applied directly to the ends of a single tube, a method to which reference has already been made in section 13.5. It is of interest to note that protons accelerated by 150,000 volts were used by Cockcroft and Walton in the first experiment in which transmutation of matter was brought about by bombarding a target with artificially accelerated particles. (Section 14.2.)

(*b*) Cyclic machines in which particles are accelerated in spirals or in circular paths by the application of periodic impulses of comparatively low voltages, or, in one instrument, by a continuously accelerating electric field. In this class of machines reference is made to the *cyclotron*, the *synchro-cyclotron*, the *betatron*, the *electron-synchrotron* and the *proton-synchroton*.

(*c*) *Linear accelerators*, machines in which, as the name suggests, the particles move in straight lines. In these instruments, although the particles may acquire energies of many MeV, extremely high voltages are not necessary.

13.7. The Cyclotron. The method employed in the cyclotron consists in giving an ion at regular intervals a succession of low voltage pushes until it acquires the speed equivalent to a high voltage. The ion, after moving at a low speed through a half-circle of small radius receives a push which sends it on at greater speed in a half-circle of larger radius ; at the end of the second half-circle, receiving another push it goes off moving still more quickly in a still greater half-circle. The process continues, half-circles being executed at greater and greater speeds and with greater and greater radii until after a few hundred or more revolutions, the ion is moving

so quickly that its energy is the same as if it has fallen through a potential difference of a few million volts. In Fig. 13.10, the curved dotted line represents a few turns of the spiral path of such an ion.



Adapted from Physical Review illustration

FIG. 13.10. *A* and *B* represent the *D*'s or dees of a cyclotron. An ion originating at *F* spirals around and around until it emerges through a thin window *W* with very high speed.

For the satisfactory operation of such a scheme, two thing are necessary: (1) The ions must be made to move in circular paths; and (2) the pushes must be properly timed. The first condition is easily realized by an application of the motor principle to which a somewhat general reference was made in connection with the deflection, by a magnetic field, of cathode rays (sections 3.4 and 3.5), positive rays (section 4.3) and alpha particles (section 12.3). Let us examine this deflection a little more carefully.

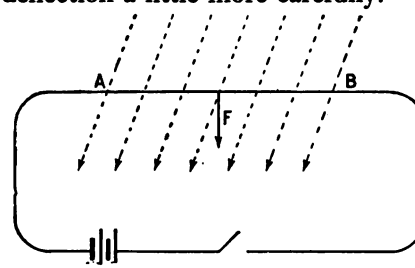


FIG. 13.11. The wire *AB* when carrying a current and lying in a direction at right angles to a magnetic field is acted on by the force at right angles to the wire and to the field.

According to the motor principle, when a wire such as *AB*, Fig. 13.11, carries a current and lies in a direction at right angles to a magnetic field (represented by the lines with arrows), it is acted on by a mechanical force in a direction perpendicular to both the wire and the magnetic lines. In Fig. 13.11, if the current, that is, the direction of positive flow, is from *A* to *B*, the force on the wire is in the direction represented by *F*.

Now a current is nothing but a flow of charges, hence a stream of any kind of electrified particles, whether cathode rays or positive ions,

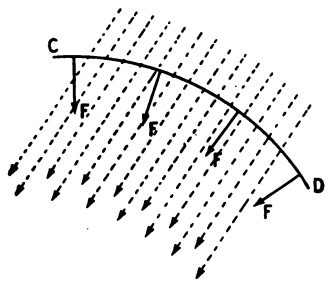


FIG. 13.12. Particles carrying a positive charge when travelling in a direct *CD* at right angles to a magnetic field are subjected to forces *F* which make the particles move in the arc of a circle.

constitutes a current. If, as in Fig. 13.12, *CD* represents the path of a stream of positive ions, there is a current in the direction *CD*. If, therefore, a magnetic field exists with lines running at right angles to the direction of motion of the ions, a mechanical force must act on the ions. Since this force is always perpendicular to both the field and the current, it is not difficult to see that the ion path must be curved as in Fig. 13.12. If the field is uniform and the speed of the ions constant, the curve is the arc of a circle.

Again, for ions moving at constant speed, the magnitude of the mechanical force is directly proportional to the strength of the magnetic field. It follows that the stronger the field, the more curved the path of the ion. On the other hand, if the magnetic field is kept constant, slowly moving ions are deflected more readily than fast ones.* The curved paths of electrified particles are beautifully illustrated by cloud-track expansion chamber photographs. Suppose that *HKLM* Fig. 13.13*a* represents a cross-section of a cloud-track chamber placed in the strong uniform magnetic field represented by the dotted lines. If a photograph is taken when an ionizing particle is moving along *CD*, the trail of ions will be curved, somewhat as shown in the top view, Fig. 13.13*b*. Actual photographs showing this are reproduced in Fig. 13.14 and Fig. 13.15. In Fig. 13.15 note: (1) the closed circles which indicate the presence of very slowly moving

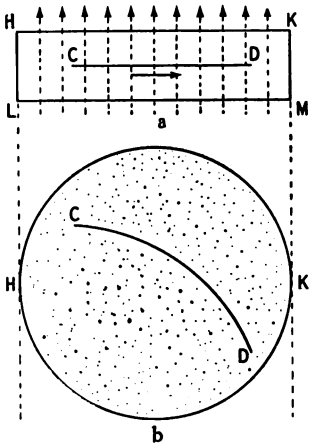
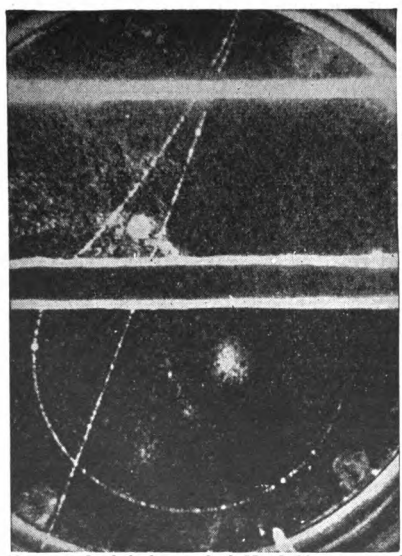


FIG. 13.13. By using a cloud chamber the curved path of a charged particle in a magnetic field may be revealed.

* A particle with charge e and velocity v is equivalent to a current ev. Application of the motor principle shows that the mechanical force deflecting the particle is Hev, where H is the intensity of the magnetic field. Since, when a particle of mass m moves with constant velocity v in a circle of radius r, the centripetal force is $\frac{mv^2}{r}$, we may write $\frac{mv^2}{r} = Hev$, or $r = \frac{mv}{He}$. Hence the smaller v, the smaller r or the more curved the path.

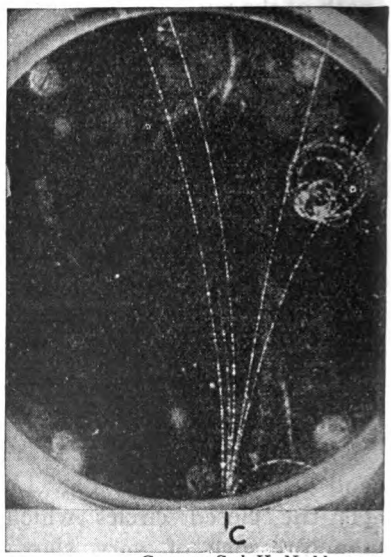
particles ; (2) the much less curved tracks, which indicate faster ions. The two opposite curvatures of the trails of the faster ions provide evidence of both positive and negative particles. (See section 15.1.)

The circular trail in the lower half of Fig. 13.14 shows clearly how, by the application of a suitable magnetic field, it is possible to make electrified particles move in circles. To deflect particles of atomic size strong magnetic fields are necessary and the construction of a sufficiently powerful electromagnet for a good cyclotron is a big job in itself. Here are a few details about the magnet used in the cyclotron illustrated in Fig. 13.16, one of the earlier instruments built under the direction of E. O. Lawrence of the University of California. The pole faces are over two feet in diameter. " The total weight of the magnetic circuit consisting of seven sections of cast steel . . . is about 65 tons." The copper coils carrying the current which magnetizes the iron weigh about nine tons and are immersed in oil. The large drum-like pieces shown in the photograph represent the outer casing surrounding these coils.



Courtesy Carl Anderson, Seth H. Neddermeyer and the Physical Review

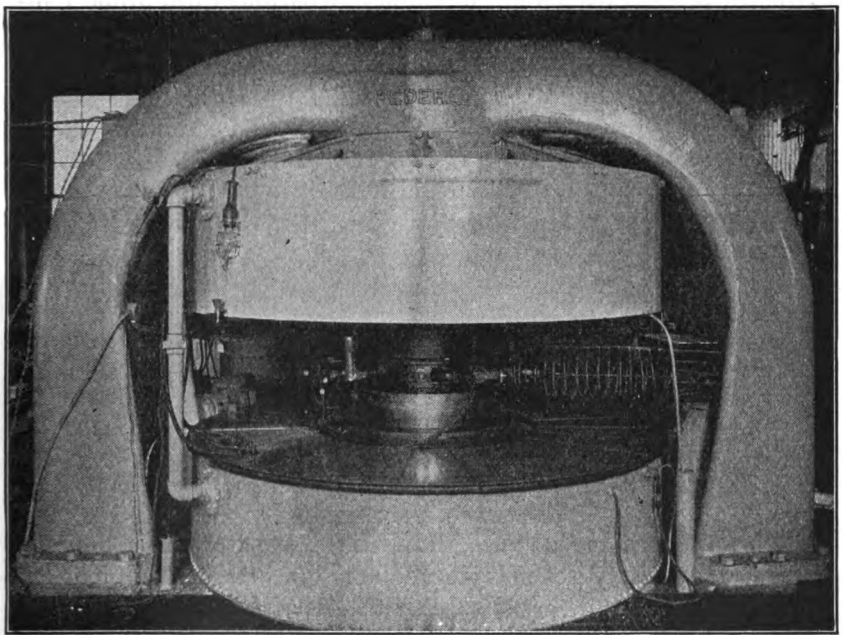
FIG. 13.14. The straight track is due to a very fast cosmic ray, the circular path in the lower half to a comparatively slow positron which originated in the lead plate. The exact circular path illustrates the effect of a uniform magnetic field on a moving electrified particle.



Courtesy Seth H. Neddermeyer

FIG. 13.15. The opposite curvatures of the tracks originating in a centre *C* show the existence of both positive and negative particles.

To make sure that the ions whirl around after the manner depicted in Fig. 13.10, the arrangement must be such that after the completion of each half-circle, an ion receives a push making it go a little faster in the next half-circle. The solution of this problem is simplified because the time taken by an ion to cover a half-circle is the same regardless of its radius. It is easy to see the reason for this. It simply means that the greater speed of the particle in a circle of greater radius just compensates for the longer path.*



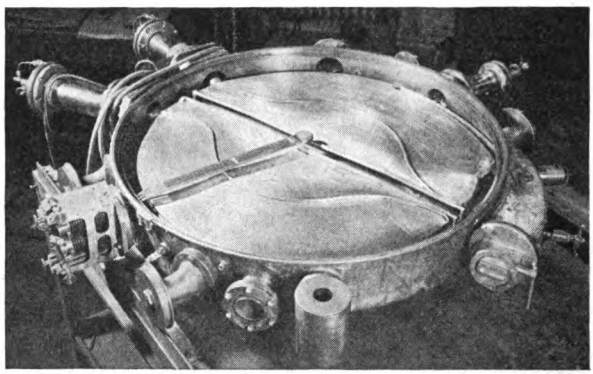
Courtesy E. O. Lawrence

FIG. 13.16. A view of one of the early cyclotrons constructed under the direction of E. O. Lawrence.

To give an ion a push at the end of each half-circle, use is made of the rapidly alternating voltages which can be maintained between two conductors by means of high frequency circuits. By such means it is not a difficult matter to maintain between the two conductors, marked A and B in Fig. 13.10, a potential difference of several

* The time to execute a complete circle $= \frac{2\pi r}{v}$. From the data given in the footnote on page 261, this may be written $\frac{2\pi m}{He}$, an expression whose value does not depend on the radius.

thousand volts which alternates from *A* positive and *B* negative to the reverse, a few million times a second. In the actual instrument *A* and *B* are hollow semicircular boxes frequently called *D*'s or dees, somewhat as shown in Fig. 13.10*b*, which lie in the region between the pole pieces of the powerful magnet. In Fig. 13.16, the position of the dees is clearly shown right at the centre of the photograph. Figs. 13.17 and 13.18, reproduced through the kindness of W. J. Henderson, are photographs of the dees used in a cyclotron constructed some years ago in the Physics Department of Purdue University.



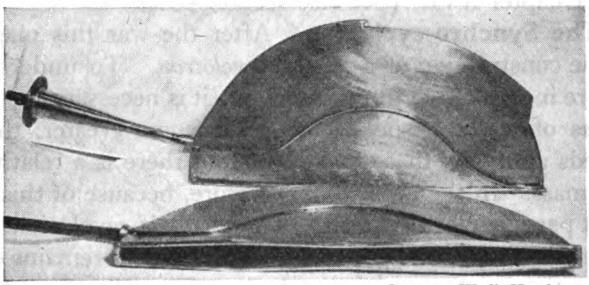
Courtesy W. J. Henderson

FIG. 13.17. The dees in the Purdue University cyclotron.

When the machine is in use, the air is exhausted from the boxes, a little gas such as hydrogen is allowed in at low pressure, and ions are created at the centre by some such device as a heated filament. The value of the magnetic field and the frequency of the oscillating electric circuit are so chosen that during the time of a reversal of voltage between *A* and *B* the ion to be speeded up moves through exactly half a circle. Whenever, therefore, an ion is pushed from *A* to *B* on the right side of the box, in the next half-cycle it will be pushed from *B* to *A* on the left, and so continue on its circular motion in paths which ever widen because of the increase in speed each half revolution. Just before the sides of the box are reached, the ions pass through a window into an observation chamber.

Sometimes the ions emerge through a thin metal window into the surrounding air. When this is the case they strike the molecules of the air and cause them to emit light of a lavender colour. The path of the ionic beam is then marked by a column of light extending for

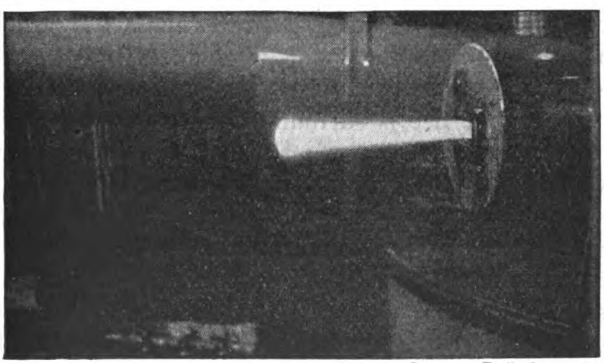
some distance from the window. This is beautifully shown in Fig, 13.19, a photograph taken by Professor Lawrence using deuterons (nuclei of heavy hydrogen) possessing some five or six million electron-volts of energy.



Courtesy W. J. Henderson

FIG. 13.18. Another view of the dees in the Purdue University cyclotron.

If a single push is given by a potential difference between the dees of 10,000 volts and an ion makes 200 revolutions, it has received 400 pushes or the equivalent of $10{,}000 \times 400$ or 4 MV. With the above cyclotron deuterons with 7 MeV were developed.



Courtesy E. O. Lawrence

FIG. 13.19. A close up photograph showing the luminescence in air caused by a beam of high energy deuterons emerging from a cyclotron.

About 1940 a giant cyclotron, originally designed to develop particles possessing 100 MeV, was under construction at the University of California. By way of contrast with Professor Lawrence's original machine, it is interesting to note that, in the giant instrument, 3,700 tons of 2-inch steel plates were used to construct the magnet, whose pole pieces have a diameter exceeding 15 feet, with a gap between

them of some 6 feet. The war interrupted the construction of this machine, but its magnet was put to use in the electromagnetic method of separating the uranium 235 isotope and so indirectly it played an important part in the harnessing of nuclear energy discussed in Chapter XVI. (See also section 4.9.)

13.8. The Synchro-cyclotron. After the war this magnet was used in the construction of a *synchro-cyclotron*. To understand the new feature incorporated in this machine, it is necessary to know that the masses of all high speed particles become greater, the nearer their speeds approach that of light, or that there is a relativistic increase in mass. In the cyclotron, therefore, because of this increase in mass, a particle takes longer to execute a half-revolution. Hence, since the frequency of the power supplied the dees remains constant, the accelerating pushes are not applied at the right moment. In the synchro-cyclotron this difficulty is overcome because, by the use of a device like a rotating condenser, the frequency of the alternating voltage applied to the dees is steadily decreased so that the pushes are always in synchronism with the motion of the particles. In a machine at Harwell, for example, which produces 180 MeV protons, " the frequency is decreased from 26 to 20 megacycles per second as the proton moves along its spiral path from centre to outside edge ". This machine, it should be added, produces about 100 proton pulses per second, each pulse lasting about 100 microseconds.

In this Harwell instrument only a single dee is used. This is possible because the dee is surrounded by an overlapping copper sheath, joined to earth, the accelerating impulses taking place in the area between the outer edges (diameters) of the sheath and the dee. Both sheath and dee are of course enclosed in a highly evacuated circular chamber, some 14 feet in diameter.

The cost of cyclotrons, with their huge magnets, becomes so great as their size is increased that they have not been built to produce energies greater than a few hundred MeV. At Liverpool, where the largest in Europe is in operation, protons with 389 MeV can be produced.

Cyclotrons, it should be noted, cannot be used for accelerating electrons.

13.9. The Betatron. In the United States, D. W. Kerst developed a machine, called the *induction electron accelerator* or *betatron*, which is of great importance to the radiologist because by means of it electrons can be speeded up until they acquire 100 MeV of energy, or even higher values. These high speed electrons may be used for

direct bombardment, or allowed to strike a target, thus creating X-rays of extremely short wave lengths.

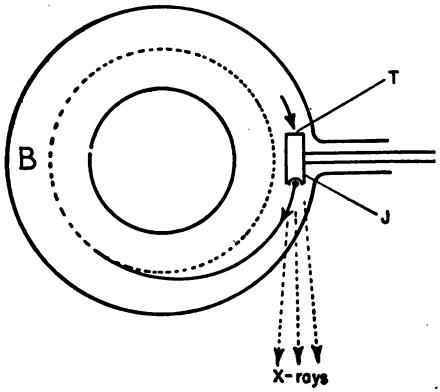
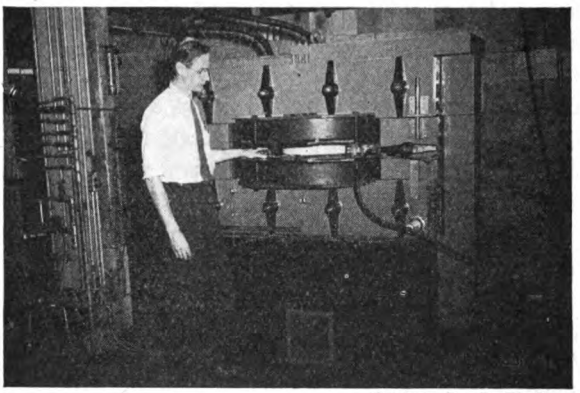


FIG. 13.20. In the betatron electrons emerging from the injector J circulate in the doughnut-shaped vessel B. (Adapted from diagram by Kerst.)

In common with the cyclotron, the electrons are constrained to move in circular paths because of a magnetic field. By means of an injector, J in Fig. 13.20, electrons from a hot filament are electromagnetically projected in a hollow evacuated box B, somewhat resembling a doughnut in shape, which lies between the poles of a magnet. Unlike the mode of acceleration in a cyclotron, the electrons are speeded up because of the induced electromotive force which results from a changing magnetic field. To obtain a suitable changing field, an alternating current is used in the electromagnet and the electrons are injected just after the current begins to rise at the beginning of a quarter-cycle. For the remainder of this quarter-cycle the current is growing and hence the strength of the magnetic field is increasing. If, now, we think of an imaginary wire in the doughnut, represented by the dotted circle in the figure, the magnetic flux through it is increasing in this quarter-cycle, and hence there is an induced e.m.f. in the wire whose magnitude is proportional to the rate at which the flux is increasing. Although there is no wire, an electron circulating in such an orbit experiences the same e.m.f. and hence is accelerated. Since this acceleration occurs in each revolution which the electron makes, it will be seen that it can acquire an extremely high speed if it can make a sufficiently large number of revolutions. This is possible only if the electron can be kept in approximately the same orbit for many revolutions. In the betatron,

electrons liberated at the injector after a few initial revolutions actually do settle down to rotation in an orbit whose radius remains constant.* The photograph reproduced in Fig. 13.21 through the kindness of D. W. Kerst, will give the reader a general idea of the appearance of a 22 MeV machine.



Courtesy Dr. D. W. Kerst

FIG. 13.21. A photograph of a 22 MeV betatron at the University of Illinois.

As long as the magnetic field is growing, there will be an induced e.m.f. with resulting acceleration of electrons. In an actual machine, the acceleration of any particular group of electrons injected into the doughnut is continued for a time not exceeding one-quarter of a cycle of an alternating current whose frequency may range from 60 cycles per second to several hundred. A good idea of the times and distances involved in a 100,000,000 eV betatron may be had from the following figures given by Coolidge and Charlton. After rotating for 1/240 second, a pulse of electrons has made 250,000 revolutions, during each of which the average induced e.m.f. was 400 volts, and has travelled a distance of some 800 miles.

* In the footnote at the bottom of page 261, it is shown that when a charged particle of mass m and velocity v rotates in a circular path in a magnetic field, the radius r of the orbit $= \frac{mv}{He}$. Since the product mv measures the momentum of a particle, it follows that the radius of the orbit will remain constant, even with changing mass and velocity, provided that the magnetic field increases in strength at the same rate as the momentum of the particle. Now the value of the momentum increases because of the force constantly acting on the electron ; this force depends on the induced e.m.f. and hence on the rate of change of magnetic flux within the orbit. It can be shown by using comparatively simple mathematics, that the radius remains constant if, at any instant, the magnetic flux within the orbit $= 2\pi r^2 H$. This condition is fulfilled in the betatron.

It should be realized that in the betatron there are two magnetic fields. In addition to the variable field for accelerating electrons provided by a central magnetic core, there is the guiding field for keeping the paths of the particles circular.

But, it will be asked, what becomes of a pulse of electrons at the end of the quarter-cycle, or whatever shorter interval they are allowed to rotate? The answer is simple enough. The electrical arrangements are such that, at the end of the time interval, a condenser is made to discharge through what are called expanding coils, so placed that the condition for a fixed orbit is destroyed and the electrons spiral out of it until they hit a target, a piece of tungsten placed on the back of the injector. For the remainder of the whole cycle of alternating current, no electrons are in the doughnut, but at the beginning of the next another pulse is injected. Hence, an intermittent series of pulses strikes the target.

At the target, X-rays originate in the usual way. Strangely enough, the target does not become hot, because for some reason the efficiency of the process of converting the kinetic energy of these extremely high speed electrons is very high, according to Mayneord being 70 per cent for 20 MeV betatrons. The output in roentgens is also high, Mayneord giving as approximate values, 100*r* per minute at 1 metre, for a 20 MeV machine, and 1,000*r* per minute for one developing 100 MeV.

It will be seen then that the betatron provides the radiologist and others with a means of developing intense beams of X-rays of very short wave lengths, and adds one more tool for experiments in radiation therapy. Moreover, it also opens up the possibility of using an electron beam itself in what we may call electron therapy, for in 1946 Kerst altered the controls in such a way as to bring the beam outside the instrument. In the United States, Laughlin, Quastler and others have published papers dealing with the biological effect of 17 and 19 MeV electrons. At the University of Illinois, 400 MeV electrons from a betatron have been used in the treatment of superficial carcinoma of the skin and other diseases.

13.10. The Electron-Synchrotron. In this instrument, as in the betatron, electrons move in an orbit of fixed radius inside an evacuated doughnut. Unlike the method used in the betatron, however, (apart from an initial acceleration brought about by a changing magnetic field) the electrons are speeded up by periodic electric impulses. These impulses are due to an electric field produced in a short resonator box which surrounds the doughnut at one place and

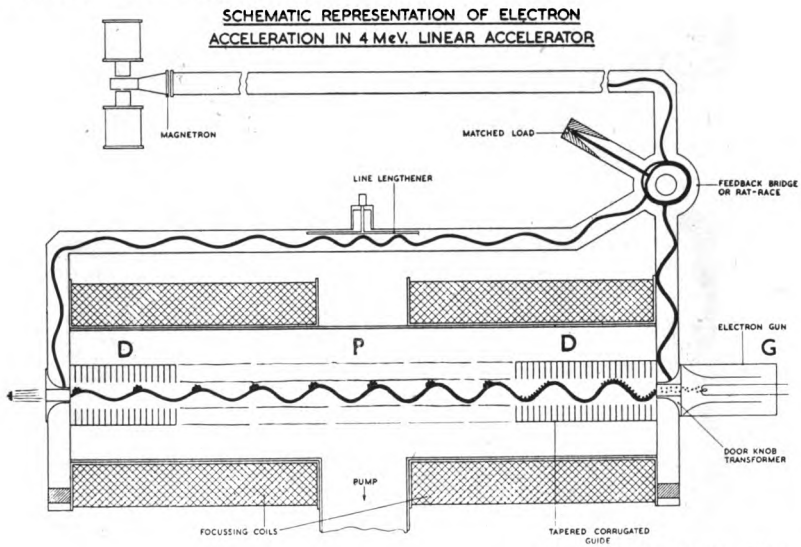
is connected to a high frequency source whose frequency is synchronized with the revolving electrons. Electron-synchrotrons have been constructed to develop energies of 30 MeV, 70 MeV, and at the University of Glasgow, there is a 300 MeV machine.

13.11. Proton-Synchrotron. Still higher energies are developed when protons instead of electrons are accelerated. At Birmingham, for example, there is a *proton-synchrotron* producing 1,000 MeV or 1 GeV. In this machine the protons revolve in an orbit of diameter 900 cm. At the Brookhaven National Laboratory in the United States, a machine called the cosmotron which develops 2,300 MeV is in regular operation. Still more energetic machines are being constructed at Berkeley, California, and for the laboratory of the European Council of Nuclear Research.

13.12. Linear Accelerator. In the field of radiology, the linear accelerator is probably the most useful of all the machines for developing electrons of high energy. In it, as its name suggests, the particles travel in straight lines, an advantage in itself, because of the ease of utilizing them at the delivery end. Although linear accelerators of different designs have been constructed, in this book attention is confined to the travelling wave type which is in use at a number of medical centres.

The particles are accelerated by and receive their energy from high frequency waves travelling along a pipe. In a 3·5 MeV unit at Harwell, the power source is a magnetron, an oscillator developing waves of frequency 3,000 megacycles per second, which delivers 2 megawatts of power in pulses of 2 microseconds duration, repeated 200 hundred times a second. The pulsed waves after travelling along a wave-guide, enter the highly evacuated corrugated pipe *P*, Fig. 13.22, along with electrons emitted by the electron gun *G*. These electrons are injected into the pipe with an initial velocity corresponding to 45 kilovolts. In the acceleration of the electrons to very high speeds, two important basic ideas are used. (*a*) When high frequency waves travel along a wave-guide (in one mode of transmission) there is a longitudinal component of the electric field. Hence there is a force acting on any electron present and moving it along the tube. (*b*) Although the phase velocity of the waves in a pipe with smooth walls exceeds the velocity of light, the velocity of the waves may be reduced and controlled by the use of a corrugated pipe, that is, one provided with metallic diaphragms, marked *D* in Fig. 13.22, with circular central holes. In the Harwell instrument there are 200 diaphragms, the dimensions of the corrugations being so chosen that

the velocity of the waves progressively increases from a low value at the entrance end to a value almost equal to that of light at the emergent end. The corrugated pipe is also so designed that at the entrance end the electrons are collected into groups or are " bunched ". Each of these pulsed bunches is then carried along by the waves with steadily increasing velocity.



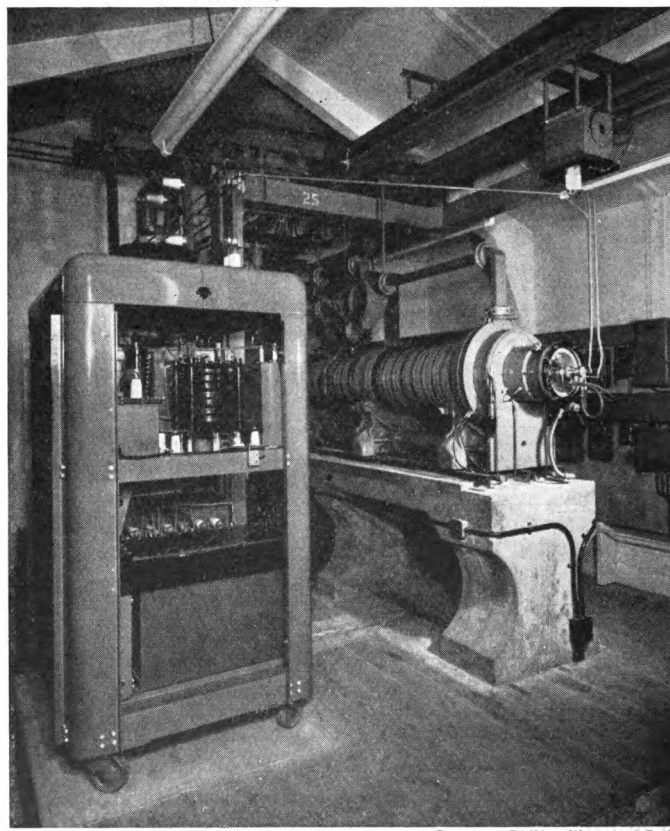
Courtesy Philips Electrical Ltd.

FIG. 13.22. Schematic diagram to illustrate electron acceleration in a 4 MeV accelerator.

Two other features of this type of accelerator should be noted. (*a*) To keep the electrons in a narrow linear path, a weak magnetic field is provided by current flowing in coils wrapped around the pipe. (*b*) To utilize efficiently the high frequency power, the waves after reaching the exit end of the corrugated pipe are led by a feed-back system to join the incoming waves from the oscillator, somewhat as is indicated in the schematic Fig. 13.22, reproduced through the kindness of Philips Electrical Ltd.

For medical applications, the linear accelerator has several advantages. (*a*) It is less temperamental in action than cyclic machines. (*b*) The length of a 4 MeV machine is only 2 metres, thus permitting a fair amount of flexibility in handling the unit. (*c*) When the electrons strike a target, the X-ray output is so high that when the accelerator is used therapeutically, the time of treatment is short, with the consequent increase in the number of patients per day

which can be treated. For example, in a 4 MeV machine developed by Philips as a hospital unit, the X-ray output is 250*r* per minute at 1 metre.



Courtesy Philips Electrical Ltd.

FIG. 13.23. Photograph of a 15 MeV linear accelerator in St. Bartholomew's Hospital, London. The electron gun is in the foreground.

The travelling wave accelerator has been used to develop maximum energies far in excess of those we have given. At Stanford University in California there is a machine 220 feet long which develops 600 MeV electrons.

The linear accelerator has also been used to accelerate protons, as in a machine installed at Harwell which develops 600 MeV.

Fig. 13.23 is a phtograph showing the external appearance of a 15 MeV accelerator installed in St. Bartholomew's Hospital by Philips Electrical Ltd. and reproduced with their kind permission.

CHAPTER XIV

TRANSMUTATION OF MATTER AND NEUTRONS

14.1. Nuclear Bombardment. The results obtained by bombarding substances with high speed particles have justified many times over the time and energy expended in the development of supervoltage machines. In this chapter reference is made to some of the important discoveries made in this way, with special emphasis on those relating to radiology. At the outset the student should become familiar with the following method of describing in symbols a nuclear interaction.

In section 3.6 it was pointed out that to describe an atom without ambiguity both its atomic weight and its atomic number must be given. Analysis by the mass spectrograph has shown in addition that on the atomic weight scale, masses of all atoms are given by numbers which depart from integers by very small amounts. With these facts in mind it is easy to see why an isotope of an element is frequently designated by the symbol ${}_aX^b$, where X is the customary chemical symbol, a is the atomic number, and b the mass number, that is, the integer which, with slight error, represents the atomic weight. Thus, ${}_1H^1$ represents ordinary hydrogen; ${}_1H^2$ or ${}_1D^2$, heavy hydrogen or deuterium; ${}_2He^4$, helium or an alpha particle; and ${}_{80}Hg^{196}$, ${}_{80}Hg^{198}$, ${}_{80}Hg^{199}$, ${}_{80}Hg^{201}$, ${}_{80}Hg^{202}$, and ${}_{80}Hg^{204}$ various isotopes of mercury.

Whenever the nucleus of an atom moving at high speed strikes the nucleus of another atom and an interaction takes place, whatever the final products, the total nuclear charge and, at least to a first approximation,* the total mass must remain constant. If, then, we write down an equation describing the nuclear reaction, the sum of the charges and of the masses on one side must equal the corresponding sums on the other side.

As an illustration, consider again the pioneer experiment of Rutherford when he obtained protons (${}_1H^1$) by bombarding nitrogen (${}_7N^{14}$) with alpha particles (${}_2He^4$). In symbols we can write

$$ {}_7N^{14} + {}_2He^4 = {}_1H^1 + x, $$

* This assumes the validity of the law of conservation of mass. Actually, in nuclear reactions, the total mass before may differ *very slightly* from the total mass after the reaction. This question is discussed and explained in section 15.3.

where x is a product which must have the mass number 17, since $14+4=1+17$; and the atomic number 8, since $7+2=1+8$. Since 8 is the atomic number or the distinguishing mark of oxygen, x must represent an isotope of this element of mass number 17, or we may now write

$$_7N^{14} + _2He^4 = _1H^1 + _8O^{17}.$$

As we have already pointed out, long after Rutherford performed this experiment, analysis by the mass spectrograph showed that oxygen has an isotope of mass number 17.

A still more abridged notation, making use of the symbol α for alpha particle, p for proton, writes the above reaction N^{14} (α, p) O^{17} which means that nitrogen of mass number 14 when bombarded with alpha particles, gives rise to an emission of protons and forms an oxygen isotope of mass 17. In nuclear reactions of this sort, it should be realized that the bombarding alpha particle actually penetrates the nucleus of the nitrogen atom, a temporary unstable compound being formed. This compound disintegrates into an oxygen atom and a proton. It should again be emphasized that out of millions of bombarding particles, only a few make collisions of such a kind that this temporary compound can be formed.

14.2. Proton Bombardment. Protons were the first artificially accelerated particles to be used in bringing about a nuclear transformation. In England, Cockcroft and Walton obtained alpha particles by bombarding a lithium target with protons, in accordance with the equation

$$_3Li^7 + _1H^1 = _2He^4 + _2He^4.$$

Although these experimenters used protons accelerated by some 150,000 volts and the transmutation can be brought about by less than 25,000 volts, the efficiency of such processes increases rapidly with the speed of the particles. For example, in one investigation it was shown that whereas for 250,000 volt protons there was one successful hit in 10^9 shots, for 500,000 volt protons, there were ten successful hits in the same number of shots. In many reactions it is desirable to have available particles speeded up by several million volts.

We conclude this section with a few other examples of proton bombardment which explain themselves.

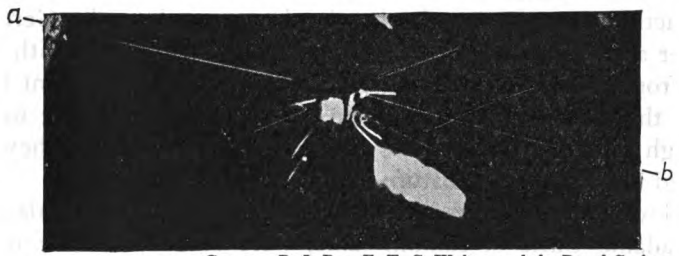
$$_5B^{11} + _1H^1 = _2He^4 + _2He^4 + _2He^4.$$
$$_{11}Na^{23} + _1H^1 = _{10}Ne^{20} + _2He^4.$$
$$_3Li^6 + _1H^1 = _2He^4 + _2He^3.$$
$$_{17}Cl^{35} + _1H^1 = _{16}S^{32} + _2He^4.$$
$$_6C^{12} + _1H^1 = _7N^{13}.$$

The last reaction is an example of *simple capture.*

14.3. Deuteron Bombardment. High speed deuterons, that is, nuclei of the atoms of heavy hydrogen, have proved of the greatest importance in bringing about nuclear transformations. At this stage we give three examples. The first is described by the equation

$$_3Li^6 + _1D^2 = _2He^4 + _2He^4.$$

Here, it will be noted, the lithium 6 isotope, on bombardment with deuterons, gives rise to alpha particles. This particular reaction is beautifully illustrated by Fig 14.1, where *a* and *b* mark the paths of the two alpha particles ejected simultaneously in opposite directions.



Courtesy P. I. Dee, E. T. S. Walton and the Royal Society

FIG. 14.1. *a* and *b* mark the paths of two alpha particles ejected simultaneously in opposite directions when a bombarding deuteron struck the nucleus of a lithium atom.

To make these long trails, the alpha particles initially must have had a great deal of kinetic energy. As this energy is a direct result of the nuclear process which takes place, it should be evident that the equation does not tell the whole story. For a complete discussion consideration must be given to the energy involved, a question considered in Chapter XV.

A second example of deuteron bombardment which the student can interpret himself is given by the equation

$$_7N^{14} + _1D^2 = _6C^{12} + _2He^4,$$

or, using the other notation,

$$N^{14}\ (d,\ \alpha)\ C^{12},$$

the symbol *d* being used for deuteron.

Another example is

$$Fe^{58}\ (d,\ p)\ Fe^{59}.$$

14.4. Bombardment by Artificial Alpha Particles. By using helium in the dees of a cyclotron alpha particles with kinetic energy of the order of many million electron-volts have been obtained. Since

the energy of alpha particles from a radioactive product such as polonium is about 5 MeV, we see what a powerful tool the cyclotron is. Moreover, not only can much faster artificial alpha particles be developed, but the intensities of the beams so obtained are the equivalent of huge amounts of radioactive material. The following is an example of an alpha ray transformation.

$$_{13}Al^{27} + _{2}He^{4} = _{14}Si^{30} + _{1}H^{1}.$$

14.5. Discovery of the Neutron. The discovery of the *neutron*, a particle of mass number 1, but without any electrical charge was the result of certain experiments in which alpha particles from a radioactive source were the bombarding particles. In Germany, Becker and Bothe, when bombarding certain substances with alpha rays from polonium observed, particularly from the element beryllium, the emission of a radiation sufficiently penetrating to pass through tolerably thick sheets of metal. This radiation they considered to be similar in nature to gamma rays.

Following up this work, in France, Joliot and his wife, the daughter of Madame Curie of radium fame, were able with more intense sources of alpha rays, to show (1) that this radiation could penetrate an inch or more of lead ; and (2) that, when it struck a substance like paraffin wax (which contains a large amount of hydrogen), protons were ejected with great energy. Note the two steps in producing the protons. Alpha rays strike beryllium ; beryllium emits this penetrating radiation, supposedly of a gamma ray nature ; the radiation strikes the paraffin wax, and protons are ejected.

In England, at Cambridge, a particle without charge and with the mass of a proton had been sought for more than once. As far back as 1920 Rutherford had made reference to the possible existence of a neutron and about the same time Harkins at Chicago had pointed out that the problem of building heavy nuclei from light was much simplified if particles of this nature were available as building bricks. Now Chadwick working at Cambridge saw that it was highly probable that at least part of this penetrating radiation from beryllium consisted of neutrons and he set out to prove it.

It was clear that the radiation in question knocked protons out of paraffin wax, and it was a simple enough matter to measure the energy of the expelled protons, by examining how far they travelled. When this was done it was seen that it was extremely unlikely that they were knocked out of the wax by a gamma ray. For this to be possible the gamma ray photon would have had to possess some fifty

million electron-volts of energy, an amount far in excess of any probable value for such radiation. On the other hand, if the radiation consisted of high speed material particles, each with a mass approximately the same as that of a proton, the behaviour of the emitted protons was exactly what was to be expected. The gamma ray hypothesis was something like assuming that a pellet of buckshot by striking a cannon ball could project it forward, whereas the (neutron) particle hypothesis made only the reasonable assumption that it was a case of one cannon ball being struck forward by another.

The ease with which the debatable radiation passed through thick layers of lead strongly suggested that the particles, if such they were, were uncharged. When a positively charged particle ploughs through matter there are strong forces of attraction between it and the negatively charged electrons in an atom near which or through which the particle is passing. In consequence, electrons are pulled out of many of the atoms in the path of the particle, the atoms are thereby ionized, and the moving charged particle is gradually slowed down as its energy is thus expended. With an *uncharged* particle, however, no such strong electrical forces exist and the slowing-down process is very much less rapid. Indeed, direct hits on the nuclei of the atoms are mainly responsible for the absorption of such a particle by the medium through which it passes. The slowing-down process of an uncharged particle, therefore, depends on two factors : (1) the degree of closeness, and (2) the masses of the nuclei. Actually the absorption is much greater in a light substance than in a heavy, because mass for mass, there are far more nuclei in the light than in the heavy substance. Moreover, the colliding particle, if of small mass, bounces off a very heavy nucleus with little loss of energy, whereas on collision with a light nucleus, such a particle transfers much of its energy to the struck particle. The fact, therefore, that lead is more transparent than light substances to the radiation in question is a strong argument in support of the hypothesis that this radiation from beryllium consists of a stream of neutrons, particles uncharged, whose masses are much less than those of the nuclei of lead atoms. If the mass of a neutron is of the same magnitude as a proton, the neutron in a head-on collision against a proton gives up all its energy to the proton, and the marked absorption of neutrons by substances containing hydrogen finds a ready explanation. (Later work, discussed in section 15.4, showed that the mass of a neutron is 1·0089 on the atomic weight scale. Compare this value with 1·00813, the mass of the hydrogen atom, and 1·00758, the mass of a proton.)

Chadwick, therefore, concluded that this extremely penetrating radiation consisted of a stream of neutrons generated according to the equation

$$_4Be^9 + _2He^4 = _6C^{12} + _0n^1,$$

where $_0n^1$ is the symbol for a neutron.

14.6. Production of Neutrons. Of the many nuclear reactions in which neutrons are liberated, the following are of importance.

(*a*) A mixture of a radioactive source of alpha particles, such as radium or radon and beryllium, which involves the above reaction has been used to a considerable extent.

(*b*) In another practical source of neutrons, a target consisting of an extremely thin layer of frozen heavy water is bombarded with deuterons. The reaction is

$$_1D^2 + _1D^2 = _2He^3 + _0n^1.*$$

(*c*) The linear accelerator can be used to generate intense pulsed beams of neutrons. When it is so used, the electron beam strikes a target which emits gamma rays of high energy. These rays are then used to bring about the photodisintegration of beryllium, the reaction being

$$_4Be^9 + \gamma = _4Be^8 + _0n^1.$$

(*d*) The phenomenon of fission and its use in an atomic reactor provides the most copious supply of neutrons. This is explained in Chapter XVI.

Of the many other nuclear reactions which release neutrons, we add three more.

$$_5B^{11} + _1H^1 = _6C^{11} + _0n^1$$
$$_4Be^9 + _1D^2 = _5Be^{10} + _0n^1$$
$$_3Li^7 + _1D^2 = _2He^4 + _2He^4 + _0n^1.$$

14.7. Energy Classification of Neutrons. In one sense all the nuclear reactions given above are incomplete because they give no information about the energy of the neutron or other liberated particles. This is an extremely important matter which is discussed in detail in section 15.3. At this stage we point out that neutrons can be obtained with energies covering a wide range and are roughly classified as thermal, slow and fast. Thermal neutrons, those in thermal equilibrium with their surroundings, at 15° C. have a mean energy of about 0·025 eV. The upper limit of energy for slow neutrons is sometimes taken as 1 eV and the lower limit for fast as 0·5 MeV, but there is no rigid classification. Handbook 55 of the U.S. National Bureau of Standards lists slow as in the range, thermal

* $_1D^2 + _1D^2 = _1H^3 + _1H^1$ has also been observed.

to 0·1 keV, intermediate from 0·1 keV to 0·02 Mev, and fast 0·02 MeV to 10 MeV.

The importance of a knowledge of energy values will appear later. Here, however, it should be noted that, if a source emitting fast neutrons is surrounded by a medium like water with its hydrogen atoms, the neutrons are slowed down because of the energy they give to the atoms on impact. For example, after some 20 collisions a 5 MeV neutron is slowed down to such an extent that its energy is only 0·1 eV. The moderator used in many nuclear reactors is a medium introduced for the purpose of slowing down fast neutrons.

14.8. Neutron Bombardment. Because of the ease with which uncharged neutrons can enter the nuclei of atoms, this particle has proved particularly valuable in bringing about nuclear reactions. An excellent illustration of this is found in the fact that whereas with the fastest alpha particles available, no disintegrations had been obtained with elements of atomic number greater than 19 before the discovery of neutrons, after the discovery it was soon shown that elements of high atomic weight, such as gold, were readily disintegrated. In this work the name of the Italian physicist Fermi, now in the United States, is outstanding.

Nuclear reactions can be brought about by both slow and fast neutrons, but the probability of a particular reaction taking place is largely a matter of experiment. The following are reactions brought about by slow neutrons.

$$
\begin{aligned}
{}_1\mathrm{H}^1 + {}_0n^1 &= {}_1\mathrm{H}^2 \\
{}_7\mathrm{N}^{14} + {}_0n^1 &= {}_6\mathrm{C}^{14} + {}_1\mathrm{H}^1 \\
{}_5\mathrm{B}^{10} + {}_0n^1 &= {}_3\mathrm{Li}^7 + {}_2\mathrm{He}^4.
\end{aligned}
$$

This is an especially interesting reaction, because Paneth and co-workers not only identified spectroscopically the small amount of helium manufactured, but also measured the volume liberated when the source of neutrons acted for a measured time. Some idea of the delicacy of Paneth's measurements is obtained from the fact that he was dealing with volumes of the order of one ten-millionth of a cubic centimetre.

14.9. Neutron Capture. One of the most interesting of nuclear reactions is what is called *simple neutron capture*. Examples are

$$
\begin{aligned}
{}_{29}\mathrm{Cu}^{65} + {}_0n^1 &= {}_{29}\mathrm{Cu}^{66} + \gamma \\
{}_{79}\mathrm{Au}^{197} + {}_0n^1 &= {}_{79}\mathrm{Au}^{198} + \gamma \\
{}_{15}\mathrm{P}^{31} + {}_0n^1 &= {}_{15}\mathrm{P}^{32} + \gamma \\
{}_{27}\mathrm{Co}^{59} + {}_0n^1 &= {}_{27}\mathrm{Co}^{60} + \gamma.
\end{aligned}
$$

These reactions are important for two reasons: (*a*) because all the products are radioactive; and (*b*) because the reactions are accompanied by an emission of gamma radiation. (See section 15.5.)

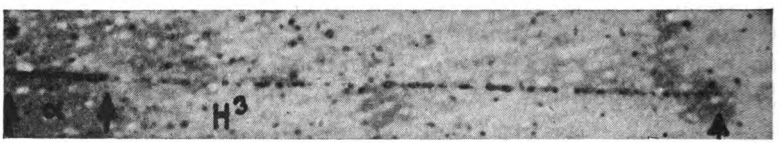
14.10. Photodisintegration. In section 14.6 reference was made to the photodisintegration of beryllium. Other examples of this type are

$$_1D^2 + \gamma = {}_1H^1 + {}_0n^1$$
$$_6C^{12} + \gamma = {}_6C^{11} + {}_0n^1$$
$$_8O^{16} + \gamma = {}_8O^{15} + {}_0n^1.$$

In photodisintegration, when neutrons are liberated the other product must be an isotope of the original atom. The product is frequently radioactive as in the last two of the above examples.

If the reverse reaction takes place, energy in the form of radiation is liberated, as in simple neutron capture. This whole question is connected with the equivalence of mass and energy, a subject discussed in detail in the next chapter.

14.11. Detection of Neutrons. Although, as has been pointed out in section 14.5, neutrons do not ionize directly, they may be detected by the use of a counter designed for alpha rays if the



Courtesy Professor Pierre Demers

FIG. 14.2. Enlargement showing the tracks in a photographic emulsion of an alpha particle (on the left) and a triton (on the right) which resulted from a neutron coalescing with a Li^6 nucleus.

ionization chamber contains the gas BF_3, boron trifluoride. When slow neutrons enter such a chamber the reaction B^{10} (n, α) Li^7 takes place.

This reaction is important for another reason, because it is the basis of a method of detecting and counting slow neutrons with an ionization chamber and counter. As already emphasized, neutrons do not themselves ionize. Suppose, however, that a beam of slow neutrons enters the ionization chamber of a counter designed for alpha rays which is filled with the gas BF_3, boron trifluoride. The B^{10} (n, α) Li^7 reaction takes place and the emitted alpha rays can be counted in the usual way. Alternately, the chamber can be filled with an ordinary gas and lined with a thin layer of boron. In either

case the number of counts is proportional to the number of alpha particles and hence to the number of neutrons giving rise to them.

Fast neutrons could be detected with the same arrangement by placing in the path of the neutron beam a thick block of paraffin to slow them down. Fast neutrons can also be detected and counted if recoil protons are generated in the gas of the chamber. Recoil protons arising from collisions in which fast neutrons give up most of their energy to protons which they hit must not be confused with protons arising from nuclear disintegrations.

Neutrons may also be detected by the use of a photographic emulsion. Fig. 14.2, a photograph reproduced through the kindness of Professor Pierre Demers, of the University of Montreal, is a good example of the photographic method of revealing tracks of particles, and also a striking visualization of the nuclear reaction

$$_3Li^6 + _0n^1 = _2He^4 + _1H^3.$$

Professor Demers reports that a slow neutron emerging from the atomic pile at Chalk River, Ontario, struck a nucleus of a Li^6 atom embedded in a photographic emulsion. The middle arrow in the photograph marks the spot where the alpha particle and the *triton*, as the nucleus of the isotope H^3 is sometimes called, originated. The alpha ray track is the denser one on the left, the triton on the right. The equivalent range *in air* of the alpha particle, as determined from its path length in the emulsion, is 1·07 cm, which means that its initial kinetic energy was of the order of 2 MeV. The actual length of the path *in the emulsion* is a small fraction of a millimetre.

Indirectly slow neutrons may be detected by the use of a film badge to which cadmium has been added. Cadmium, like boron, has an exceptionally high cross section for neutron capture. The film is affected by the resulting radiation. (See Appendix A.)

14.12. Neutron Therapy. There is ample evidence that biologically neutrons are of very great importance. Although, as we have seen, a neutron being uncharged does not ionize directly, indirectly it may cause intense ionization in a very short distance. For example, in passing through tissue with its high percentage of hydrogen, many neutrons are stopped (or slowed down) by direct hits (or less direct collisions) against protons. These protons then begin to move with the energy imparted to them by the neutrons, and being heavy charged particles cause intense ionization as they are slowed down. Since we have good reasons for believing that ionization is the primary cause of biological changes, it is only reasonable to expect strong biological reactions with neutron bombardment.

The protons liberated in the following reaction involving nitrogen in tissue may also have biological significance

$$_7N^{14} + _0n^1 = _6C^{14} + _1H^1.$$

Another reaction which may be of importance biologically because of the gamma radiation is

$$_1H^1 + _0n^1 = _1H^2 + \gamma.$$

At Brookhaven experiments making use of the B^{10} (n, α) Li^7 reaction have been carried out with patients suffering from glioblastoma. Boron, administered intravenously, after a short time has a marked concentration in the brain tumour. The patient is then irradiated with slow neutrons and possible effects resulting from the alpha radiation are sought.

Dosage. The only exact method of estimating the dose delivered in neutron therapy is to find the energy expended per gram of tissue. Hurst of the U.S. Oak Ridge National Laboratory has shown that the gas ethylene has the same energy equivalence as wet tissue or that " ethylene is tissue equivalent for fast neutrons ". He has described a proportional counter in which, due to the passage of fast neutrons, ionization is produced by recoil protons in a chamber containing ethylene. Hurst states that by means of this counter absolute dose in ergs per gram may be evaluated for fast neutrons.

In actual practice, however, use has been made of the *n unit* which is defined as " the dose of fast neutrons which, when incident on a thimble ionization chamber of specified characteristics, produces the same amount of ionization as would one roentgen of X- or gamma radiation ". (B.S.I. Glossary.) See also p. 314.

CHAPTER XV

ARTIFICIAL RADIOACTIVITY, MASS AND ENERGY

15.1. The Positron. In section 4.1 it was stated that at all times there are a few stray ions present in air. The study of the cause of the feeble conductivity arising from these ions led to the conclusion that the earth's atmosphere is traversed by a radiation of as yet unknown origin, coming in " from out of the everywhere into here ". This radiation is now called *cosmic rays*. Hundreds of investigations have been made and hundreds are in progress, concerning the nature of these rays. Although much information has been found, the question of cosmic rays presents many problems still unsolved and in this text details are out of place. One result of these researches, the discovery of the *positron*, is important in radiological physics.

Figure 13.15 reveals a phenomenon which frequently occurs when a cosmic ray strikes a substance like a metal plate. As is seen in this photograph, a shower of electrified particles, originating as a result of the impact of a cosmic ray, has emerged from a centre marked *C*, in the material surrounding the cloud-track chamber. When this photograph was taken, the particles had to traverse a magnetic field, and hence the curvature in opposite directions strongly suggests that there are two kinds, one with a positive charge, the other with a negative. The only known negatively charged particle is an electron, but we have become familiar with two positive particles, alpha rays and protons. The assumption that the path curved in one direction is caused by an electron is greatly strengthened by the appearance of the trail, because the little dots representing ions look exactly the same as those obtained with beta rays and fast electrons. Moreover, estimates of the energy of such particles, based on the measured curvature of their tracks (and the assumption that they are electrons), lead to values in agreement with observations of their ionization and their penetrating powers. We get into difficulties, however, when we try to ascribe the trail of opposite curvature to either an alpha particle or a proton. This trail also looks exactly like that of an electron, and not at all like the heavy continuous line representing the trail of an alpha particle or of a proton. If, disregarding this similarity to the path of an

electron, the particle is assumed to be either an alpha ray or a proton and its energy is calculated making use of the amount of curvature, values are obtained far too small to account for the observed penetrating power. All the evidence, therefore, indicates that the trail is caused by a positively charged particle of mass comparable with that of an electron. When cosmic ray cloud-track photographs were first taken, no such particle was known to exist, but this was the conclusion to which Anderson in the United States, in 1932, and not long afterwards Blackett in England were driven. This new particle was given the name *positron*.

Another good example of the track of a positron is shown in Fig. 13.14.

Although the positron is, in many ways, the counterpart of the electron, it differs from it in one important respect, because unlike the ubiquitous stable electron, the positron is an extremely short-lived unstable particle. If electrons are about, a positron and an electron will embrace giving rise to gamma radiation, again a matter more fully explained in the next chapter.

15.2. Artificial or Induced Radioactivity. In 1934 Mme. and M. Joliot, working in France, found that aluminium foil, which had been bombarded with alpha rays for a few minutes, emitted positrons *after the bombardment had ceased.* The foil could be removed from the source of alpha rays—taken into another room altogether—and when brought near a charged electroscope, caused it to lose its charge just like a natural radioactive body. The aluminium soon lost its acquired radioactivity, decreasing to half-strength in about three minutes, but the effect was unmistakable. Aluminium can be made temporarily radioactive by bombardment with alpha rays. What exactly happens?

An examination of the transmutation products resulting from the bombardment of aluminium with alpha rays, shows that *during the bombardment* sometimes protons are emitted, sometimes neutrons and positrons. The proton emission is readily explained by the transformation

$$_{13}Al^{27} + {}_{2}He^{4} = {}_{14}Si^{30} + {}_{1}H^{1}.$$

To account for a neutron emission, the following transmutation must take place.

$$_{13}Al^{27} + {}_{2}He^{4} = {}_{15}P^{30} + {}_{0}n^{1}.$$

In this case, the products of the transformation are a neutron and an element which must be phosphorus, because its atomic number is 15. Phosphorus is a well-known element with a stable isotope of mass number 31, but it has no known stable isotope with mass number 30. Mme. and M. Joliot, therefore, concluded that this isotope of phos-

phorus is unstable or radioactive, emitting positrons when it " explodes ". What happens then is this. The original bombardment of the aluminium manufactures a certain amount of ${}_{15}P^{30}$. On ceasing fire with the alpha rays, the foil is removed and embedded in it are these new unstable or radioactive atoms. When they explode, they shoot off positrons.

Since a positron has an almost negligible mass and one unit positive charge, the nucleus left behind after the explosion has practically the same mass as before, but an atomic number one less. In the case of ${}_{15}P^{30}$ the nucleus left, therefore, must have an atomic number of 14, hence it must be silicon.

We may write

$$ {}_{15}P^{30} = {}_{14}Si^{30} + {}_{1}e^{+}, $$

where ${}_{1}e^{+}$ is the symbol used for a positron.

The half-period of P^{30} is a little less than three minutes.

To distinguish an unstable, radioactive isotope of an element from a stable one, particularly when the element occurs in nature only in its stable form, the prefix *radio* may conveniently be used. Since, however, the same element may have more than one radioactive isotope, the mass number should also be specified. The element phosphorus, for example, has a radioactive isotope of mass number 32, as well as of 30.

Radiophosphorus^{32}, or ${}_{15}P^{32}$, is of much greater importance to the radiologist than ${}_{15}P^{30}$ because its half-period of 14·3 days is so much longer. The following equations describe a few of several ways in which it can be prepared.

$$ {}_{16}S^{32} + {}_{0}n^{1} = {}_{15}P^{32} + {}_{1}H^{1} $$

$$ {}_{15}P^{31} + {}_{1}D^{2} = {}_{15}P^{32} + {}_{1}H^{1} $$

$$ {}_{14}Si^{29} + {}_{2}He^{4} = {}_{15}P^{32} + {}_{1}H^{1}. $$

When ${}_{15}P^{32}$ disintegrates, beta rays are emitted, hence ${}_{16}S^{32}$ must be the final stable product, in accordance with the relation

$$ {}_{15}P^{32} = {}_{16}S^{32} + {}_{1}e^{-}. $$

A second interesting example of a radioelement is ${}_{11}Na^{24}$ which may be manufactured by methods such as the following:

$$ {}_{11}Na^{23} + {}_{1}D^{2} = {}_{11}Na^{24} + {}_{1}H^{1} $$

$$ {}_{12}Mg^{24} + {}_{0}n^{1} = {}_{11}Na^{24} + {}_{1}H^{1} $$

$$ {}_{12}Mg^{26} + {}_{1}D^{2} = {}_{11}Na^{24} + {}_{2}He^{4} $$

$$ {}_{11}Na^{23} + {}_{0}n^{1} = {}_{11}Na^{24} + \text{gamma}. $$

When radiosodium^{24} disintegrates, with a half-period of 14·8 hours, $_{12}Mg^{24}$ is the stable product and beta and gamma rays are liberated. In symbols we write

$$_{11}Na^{24} = {}_{12}Mg^{24} + {}_{1}e^{-} + \gamma.$$

Radiosodium^{24} may readily be made in quantities which are the equivalent of thousands of dollars worth of radium.

In passing it is interesting to note that sodium has in all the following five isotopes, four of them radioactive with half-periods given in brackets: Na^{21} (23 seconds); Na^{22} (3·0 years); Na^{23} (stable); Na^{24} (14·8 hours); and Na^{25} (62 seconds). There is nothing particularly unique about this, for it applies to many other elements. Carbon, for example, has in all three radioactive and two stable isotopes.

Because of the many uses, in medicine and other fields, to which radioactive nuclides are put, their production is now almost a major industry. A recent announcement (February, 1955) that Britain is now producing consignments of isotopes at the rate of 20,000 a year gives some idea of the extent to which they are being used.

Although some isotopes are manufactured by the methods described above, the atomic reactor discussed in the next chapter is the chief source of supply. Some of the isotopes useful in medicine are listed in Table XXVII.

TABLE XXVII—SOME ISOTOPES IN USE IN MEDICINE

Isotope	Half-period	Radiation*	*k* factor
H^{3}	12·4 yr	β (0·018 max)	
C^{14}	5,570 yr	β (0·015 max)	
Na^{24}	15 hr	β (1·4 max, 0·54 mean) γ (1·38, 2·76 ; mean 2·07)	18.85
P^{32}	14·3 d	β (1·7 max, 0·7 mean)	
Fe^{59}	47 d	β (0·46, 0·26 max, 0·12 mean) γ (1·10, 1·30 ; mean 1·20)	6·55
Co^{60}	5·3 yr	β (0·31 max, 0·12 mean) γ (1·17, 1·33 ; mean 1·25)	13·53
Sr^{90}	19·9 yr	β (0·6 max)	
I^{131}	8·0 d	β (0·6 max ; 0·4 mean) γ (0·364, 0·638, 0·72 ; mean 0·4)	2·25
Xe^{133}	5·3 d	β (0·34 max) ; γ (0·085)	
Tm^{170}	127 d	β (0·89, 0·97 max) ; γ (0·084)	
Ta^{182}	111 d	β (0·50 max) γ (0·22, 1·13, 122 ; mean 1·13)	6·13
Au^{198}	2·7 d	β (0·97 max, 0·35 mean) γ (0·411 ; mean 0·42)	2·42

* The energy value, in MeV, is given in brackets. For β rays, max is the maximum energy, mean the average.

The meaning of *k* factor is explained in section 15.11.

15.3. Mass and Energy. The work on disintegration and transmutation has shown that the nuclei of atoms must be complex in structure. In present day physics one of the important problems is the elucidation of this structure. It is not our purpose to go into details about the information which has been obtained, but there is one question relating to nuclear structure and nuclear transformations which is so fundamental that some explanation of it must be given. This has to do with the equivalence of mass and energy.

In section 14.1 it was pointed out that, in equations dealing with nuclear reactions, the sum of the mass numbers on each side of the equation must be the same. *This, however, is true only to a first approximation.* If use is made of the accurate values of atomic weights found by the mass spectrograph, a few of which are listed in Table IV, section 4.8, a very slight discrepancy between the sums is found. As an example consider again the reaction

$$_3Li^7 + _1H^1 = _2He^4 + _2He^4.$$

If we set down in a kind of balance sheet, the accurate mass values, we see at once that the sum on the right side of the equation is distinctly less than the sum on the left. The discrepancy is not great,

BEFORE	AFTER
Mass of $Li^7 = 7{\cdot}0182$	Mass of $He^4 = 4{\cdot}0039$
Mass of $H^1 = 1{\cdot}0081$	Mass of $He^4 = 4{\cdot}0039$
Sum $= 8{\cdot}0263$	Sum $= 8{\cdot}0078$

being only 0·0185, but it is far too large to be described to experimental error. In the transaction, apparently mass has been lost. What has become of it?

The answer to a question of this kind had already been given by Einstein, who showed that *every form of energy has an equivalent mass.* It is a wrong, although a very common, idea, to consider mass and matter synonymous. It is perfectly correct to state that inert matter has mass, but the converse is not necessarily true, because all mass is not associated with matter. Energy, too, has mass. A photon, for example, has mass; and the mass of a proton is greater when it is moving than when it is at rest by the mass equivalent of its kinetic energy.

In symbols, Einstein's law is written

$$E = mc^2 \quad \text{or} \quad m = \frac{E}{c^2}$$

where E represents the amount of energy, c is the velocity of light, and m the equivalent mass. Let us put the matter in numbers.

The mass of a hydrogen atom $= 1{\cdot}66 \times 10^{-24}$ gm, and $c = 3 \times 10^{10}$ cm per sec. If, therefore, it was possible to annihilate a hydrogen atom, although inert matter would disappear, the mass would now be associated with an amount of energy given by

$$E = 1{\cdot}66 \times 10^{-24} \times 9 \times 10^{20} \text{ ergs.}$$

If this energy is expressed as V electron-volts, then we write (see section 3.5)

$$\frac{V}{300} \times 4{\cdot}8 \times 10^{-10} = 1{\cdot}66 \times 10^{-24} \times 9 \times 10^{20},$$

from which

$$V = 933 \text{ MV.}$$

Thus, we may state that the disappearance of about 1 unit of matter on the atomic weight scale should release about 933 MeV ; hence the disappearance of 0·001 of a unit releases about 0·933 MeV. Approximately we may use 1 MeV as the equivalent of 0·0011 of an atomic weight unit.

On this view, then, *conservation of mass holds only if we include the mass equivalent of any energies involved in a transaction.* The truth of this was proved by direct experiment for the reaction

$$_3\text{Li}^7 + {}_1\text{H}^1 = {}_2\text{He}^4 + {}_2\text{He}^4.$$

In one experiment it was shown that when the bombarding proton had 300,000 eV of kinetic energy each of the emitted alpha particles is ejected with 8·7 MeV of kinetic energy. When these energy values are taken into consideration and Einstein's law is applied, there is agreement to a high order of accuracy between the total mass on one side of the equation and the total on the other. Our balance sheet now is written.*

BEFORE

Mass of lithium^7 atom		7·0182
Mass of bombarding hydrogen^1 atom		1·0081
Mass equivalent of 300,000 eV	$= \frac{300{,}000}{933{,}000{,}000}$	·0003
Total		8·0266

* The objection may be made to the numbers given in the balance sheet that the mass of the *nucleus* should be used, not that of an *atom*. This is perfectly true, but no error is introduced into the calculations because the atomic mass is substituted for the nuclear mass on each side of the equation. Putting it in another way, we have added to the nuclear masses on each side the masses of four extranuclear electrons.

	After
Mass of 2 helium atoms $= 2 \times 4{\cdot}0039$ - - - -	= 8·0078
Mass equivalent of 8,700,000 eV - $= \frac{8{,}700{,}000}{933{,}000{,}000}$	= ·0093
Mass equivalent of 8,700,000 eV - - - - -	= ·0093
Total - - - - - - - - - -	8·0264

15.4. Mass of the Neutron. By applying the law of conservation of energy (or of mass) in its exact form to the nuclear reaction

$$_1D^2 + \gamma\ (2{\cdot}62\ \text{MeV}) = {}_1H^1 + {}_0n^1,$$

it is easy to evaluate the mass of a neutron. On the left hand side of this equation, the mass is 2·01471, for D^2, plus 2·62/933, or 0·00281, the mass equivalent of 2·62 MeV, making a total of 2·01752. On the right hand side, we must record 1·00813 for H^1, plus x, the mass of the neutron, plus the mass equivalent of the energy of motion of the disintegrated particles. Now, by measuring the amount of ionization produced by a proton, Chadwick and Goldhaber showed that the energy of motion of both the proton and the neutron in this reaction was about 0·5 MeV. Since this amount has a mass equivalent of 0·00053 unit, the total to be recorded on the right side of the equation is

$$1{\cdot}00813 + 0{\cdot}0053 + x, \quad \text{or} \quad 1{\cdot}00866 + x.$$

Hence,

$$2{\cdot}01752 = 1{\cdot}00866 + x,$$

or $x = 1{\cdot}0089$, to 5 significant figures.

15.5. Emission of Gamma Rays in Nuclear Reactions. In the proton-lithium reaction, the form of the energy released was kinetic, but this is not the only kind which can appear. As we have seen in the examples of simple neutron capture given in section 14.9, sometimes gamma radiation is released. If the exact masses of the nuclides involved are known, it is a simple matter (using $E = mc^2$) to calculate the amount of radiation energy. Consider, for example, the gamma radiation emitted in the reaction

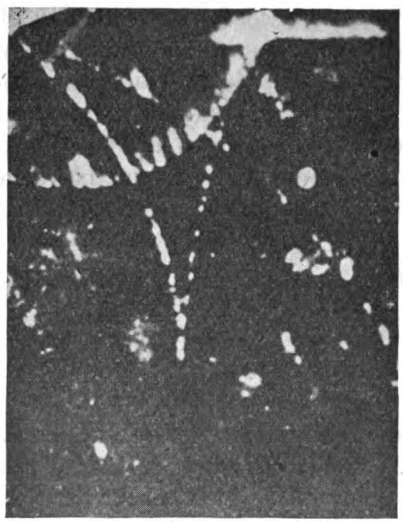
$$_5B^{11} + {}_1H^1 = {}_6C^{12}.$$

Since the mass of $B^{11} = 11{\cdot}0128$
and the mass of $H^1 = 1{\cdot}0081$

or the total $= 12{\cdot}0209$
and since the mass of $C^{12} = 12{\cdot}004$,

we see that the lost mass, or more accurately, the loss of mass associated with matter = 0·017 unit. Hence, energy is released to the extent of $17 \times 0{\cdot}93$ or about 16 MeV. Experimentally, when this reaction takes place, an emission of gamma rays is observed, with energy reaching a maximum value of 16·6 MeV. From observation and measurement of the energy of gamma rays emitted in such a reaction, valuable information is obtained about the various states or conditions in which the nucleus of a stable atom may exist.

This emission of gamma rays must not be confused with the gamma radiation from a radioelement. In that case, an unstable nucleus is formed as a result of the nuclear reaction. When, subsequently, such a nucleus explodes because of its instability, gamma rays are sometimes emitted.



Courtesy Mme. and M. Joliot

FIG. 15.1. An electron-pair. The two tracks curved in opposite directions and emerging from the same point are the paths of a positron and an electron created by the disappearance of a gamma ray.

15.6. Pair Production. We have seen in section 14.10 that the photon of a gamma ray may bring about the disintegration of a stable nucleus. In this case, the photon disappears, its energy being absorbed by the disintegrating nucleus. Earlier in this book, emphasis was laid on the fact that, in the photoelectric effect, a photon completely disappears, its energy being used to eject the photoelectron. A third way in which a photon may completely dis-

appear provides a striking example of mass associated with energy appearing as equivalent mass associated with material particles. In what is known as *pair production*, a photon, when in a region close to the nucleus of an atom, disappears, giving rise to the birth of an electron and a positron. The phenomenon is beautifully shown in Fig. 15.1.

For pair production to take place, the photon must possess sufficient energy and it must be in the field of the nucleus of an atom, the heavier the better. It is easy to estimate the necessary minimum amount of energy, since it is well known that the rest or slow-speed mass of an electron (and a positron) is 0·00055 unit on the atomic weight scale. Since this is the energy equivalent of $0{\cdot}00055 \times 933$ or about 0·51 MeV of energy, at least $2 \times 0{\cdot}51$ or 1·02 MeV is necessary to give birth to an electron pair. To produce a pair giving rise to tracks like that shown in Fig. 15·1, the original photon must have had energy considerably in excess of 1·02 MeV, the excess over this amount going into the kinetic energy of the particles.

When photons of sufficiently high energy are used, pair production is of importance if tissue is radiated. In section 10.7, it was pointed out that, as we use higher and higher potential differences to generate X-rays, absorption due to recoil electrons becomes of greater importance than that due to the photoelectric effect. From 200 kilovolts up, recoil electrons predominate. If the radiation consist of photons with energy around 50 MeV, pair production is the most important factor causing absorption.

As might be expected, the converse to pair production can take place and has been observed experimentally. When a positron and an electron come together, they disappear giving birth to energy in a process which can legitimately be called annihilation of matter. Obviously the union produces 1·02 MeV of energy in the form of gamma radiation.

15.7. Medical Uses of Isotopes. The various ways in which radioactive isotopes are used in medicine may be grouped into three classes : their uses as (*a*) tracers or indicators or spy atoms ; (*b*) therapeutic agents ; (*c*) in diagnosis. The use of radioactive materials as indicators depends on two facts. (1) The ionization method of detecting and measuring small quantities of radioactive substance is so sensitive that it is possible to measure quantities millions of times less than the smallest amount detectable even by the spectroscope. Hevesy and Paneth, who were pioneers in the use of radioactive elements as indicators, state that whereas " spectroscopy can often

not only detect, but even measure, much smaller amounts, down perhaps to 10^{-9} or 10^{-10} gm . . . only the methods of radioactivity are able to determine quantities of matter of the order of, say, 10^{-17} gm ". (2) Stable isotopes and unstable or radioactive isotopes of the same element have identical chemical properties, and, therefore, cannot be separated by chemical means.

Now long before the discovery of artificial radioelements it was realized, notably by Hevesy and Paneth, that if a small amount of a radioactive isotope was mixed with a large amount of a stable isotope of the same element, the activity of the radioactive portion would reveal the presence of the whole quantity. Bismuth and radium E, for example, are isotopes with the same atomic number 83, and if these substances are mixed, it is impossible to separate them by chemical means. But, wherever the mixture is, its presence can be detected by the signals which the unstable atoms of radium E send out in the form of ionizing beta radiations. Moreover, because of the extreme sensitivity of the ionization test, only a very small amount of the radioactive tracer or indicator is needed. This particular example has been given, because bismuth is used in the treatment of syphilis, and by the addition of radium E, it was possible to investigate " the rate at which different bismuth compounds are resorbed after injection " (Hevesy and Peneth).

P^{32}, because of its fairly long half-period and its importance in body metabolism has been used in the study of many problems. A small amount of the radioactive element, mixed with sodium phosphate, for example, is introduced into the body by the mouth and the subsequent behaviour of the phosphorus traced by the use of a Geiger or scintillation counter. It has been shown that the role of phosphorus in bones, for example, is a dynamic process ; that is, atoms of this element are constantly being replaced by the arrival of fresh atoms.

The same methods applied to plants have shown that in the leaves of maize and sunflowers, phosphorus atoms wander about, the same atom moving from one leaf to another in the course of a few days.

Although the half-period of Na^{24} is much shorter than that of P^{32}, it also has proved useful as an indicator. Common salt, to which a little Na^{24} has been added, can be detected in a hand ten minutes after it has been swallowed ; and when a solution of common salt is injected intravenously in one hand, twenty seconds later sodium appears in the other.

A good example of the use of Na^{24} is given by a somewhat extensive investigation by Smith and Quimby. In this work normal saline

was injected intravenously into some 200 patients with peripheral vascular disease, and " the circulation of the blood was traced by following (with a Geiger-Mueller counter) the sodium it carried ".

The actual amount of active material necessary for tracer work is extremely small. For example, 170 microcuries of P^{32} in a solution of Na_2HPO_4 injected intravenously might be used.

By contrast, when the use is therapeutic, quantities ranging from a few to many thousand millicuries are used.

15.8. Isotopes in Therapy. In treatment, isotopes are used in a number of different ways.

(*a*) In additon to the use of radium needles and radon seeds for interstitial treatment (see section 12.10), there are now available such sources as tantalum^{182} in the form of short pieces of wire of diameter 0·2 mm with a platinum sheath of thickness 0·1 mm ; grains of gold^{198} of average mass 6·5 mgm ; and small pieces of activated cobanic wire (cobalt 45 per cent, nickel 55 per cent). When these isotopes are used, the treatment is due to gamma rays. In the case of tantalum^{182} with its period of 111 days, the seeds are left in tissue for a predetermined time, but with gold^{198}, with its short period of 2·1 days, they may be left permanently in the tissue.

(*b*) Colloidal gold^{198} may be inserted in an organ like the bladder.

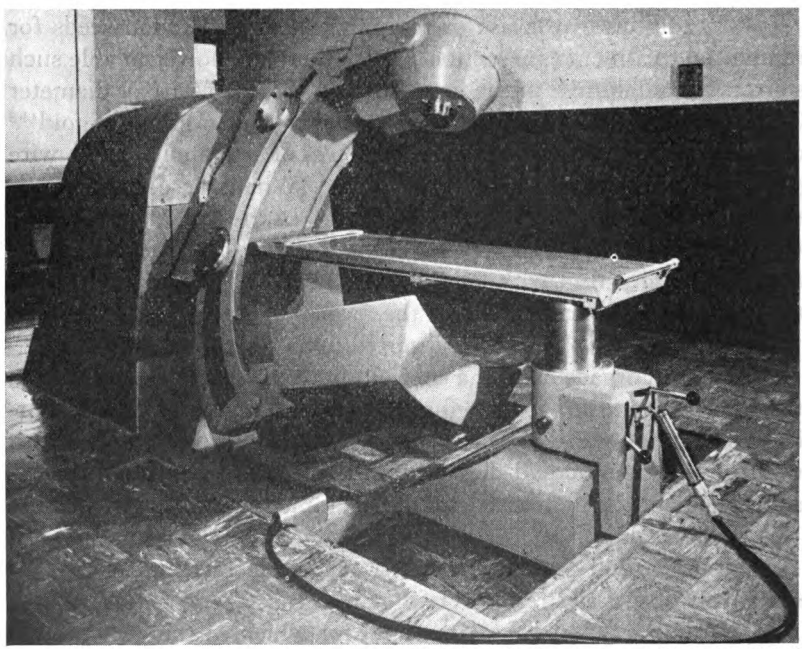
(*c*) Certain organs exhibit a special uptake for particular elements, the thyroid gland for iodine, for example. Hence, if I^{131} is administered to a patient, it is selectively concentrated in this gland, with resulting therapeutic and diagnostic action. (The way in which the active material is distributed can be examined, as we saw in section 12.9, by a scanning device.)

Astatine^{211} (half-period 7·5 hours), an alpha ray emitter, is also selectively absorbed in the thyroid gland.

(*d*) In beta ray superficial therapy, for which in the past radium plaques were used, isotopes emitting beta rays are a convenient substitute. Phosphorus^{32}, in a flexible plastic material in which phosphorus was incorporated before activation, is one example. Strontium^{90} and cerium^{144} have also been used.

(*e*) In section 12.10 reference was made to the use in teletherapy of a source of radium containing several grams, and in section 13.1 the advantages of using ultra-penetrating radiation for deep-seated therapy were pointed out. The ability to manufacture artificial radioactive sources of strength many hundred times greater than that of a few grams of radium has almost revolutionized teletherapy. The most outstanding example is cobalt^{60} whose use is to some extent

replacing the elaborate deep therapy X-ray equipment. A typical example of a cobalt unit is one in use at Saskatoon, Canada, of strength about 1,000 curies. The actual source in this unit consists of 25 discs of activated cobalt, each 2·55 cm in diameter and 0·052 cm thick, placed one on top of the other. The source of course is heavily protected with surrounding metal. The photograph shown in Fig. 15.2 reproduced through the kindness of Mr. R. H. Bull of Atomic Energy of Canada Limited, shows the head of a unit in the Theratron mounting, one of which is in use at the Mount Vernon



By courtesy of R. H. Bull, Atomic Energy of Canada, Limited

FIG. 15.2. The theratron mounting for a cobalt^{60} unit.

Hospital in London. This design of mounting makes it possible to rotate the active source through 360° and also in an arc of 45° in a plane perpendicular to the plane of rotation.

15.9. Isotopes in Diagnosis. Although the therapeutic use of isotopes has been more marked than the diagnostic, the following gives some idea of the possibilities of their use in diagnosis.

(*a*) Radiographs may be made with such sources, provided the rays emitted have a suitable penetration. For the examination of

flaws in steel castings (non-destructive testing) cobalt^{60} or iridium^{192} can be used. For radiographs of the human body, where fairly soft

By courtesy of W. V. Mayneord and H. J. D. Ireland

FIG. 15.3. Radiograph of an ankle taken by H. J. D. Ireland of the Royal Marsden Hospital, London, with a xenon^{133} source.

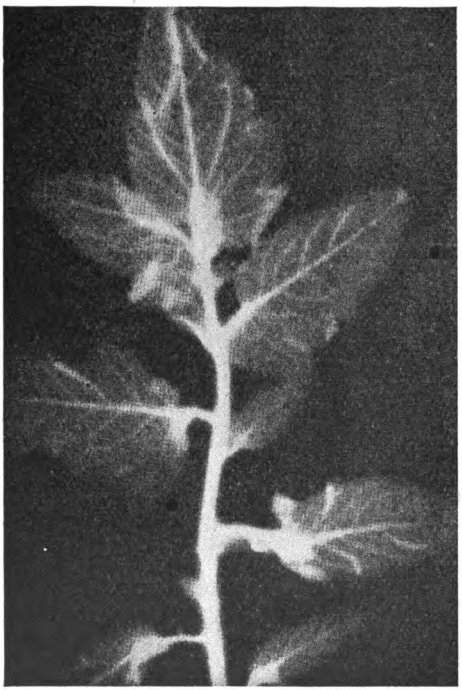
rays are necessary, thulium^{170} which emits gamma rays of energy 84 keV and xenon^{133} emitting 80 keV have been used with some success by Mayneord and his colleagues, and others.

The photograph reproduced in Fig. 15.3, through the kindness of Prof. W. V. Mayneord and Mr. H. Ireland of the Royal Marsden Hospital, shows the possibilities of this method. In the United States, Untermayer of the Argonne National Laboratory has described recently what is called a portable thulium^{170} X-ray unit. Although there is little likelihood of this method giving radiographs as satisfactory as those made with standard X-ray equipment, it has obvious advantages in places where no X-ray units are available or can be transported.

(*b*) A tele-autograph taken by Mayneord with his scanning equipment revealed the existence of a lesion in the head of a patient who had been given iodine by mouth for the treatment of a primary

lesion in another part of the body. Radiographs had given no evidence of this secondary lesion.

(*c*) As a result of work done by a number of investigators in the United States and in Britain, there is some evidence that when phosphorus^{32} is administered to patients with brain tumours, the uptake in the tumour is greater than in normal brain tissue. This suggests a possible new method of locating the exact position of the tumour.



Courtesy Radiology and Dr. J. M. Cork

FIG. 15.4. Autoradiograph showing the distribution of radiophosphorus in the leaf of the tomato plant. (Original by Dr. Perry Stout.)

15.10. Detection and Autoradiography. The above outline of some of the uses of isotopes should show how important it is to have sensitive means of revealing their presence in the body. Reference has already been made to the use of Geiger and scintillation counters for external examination and for testing small samples of tissue which have been treated chemically to make a radioactive solution. One other method of detection, *autoradiography*, is of great value for some purposes. In this method a thin specimen, possibly a histo-

logical section, is placed in contact with a photographic emulsion. Since the emulsion is affected by the beta rays emitted by the radioactive material in the specimen, the developed image provides a permanent record of the presence and the distribution of the active material.

A good example of the use of this method in detecting tracer atoms of phosphorus^{32} is nicely illustrated in Fig. 15.4, a photograph originally taken by Dr. Perry Stout and reproduced through the courtesy of *Radiology* and Dr. J. M. Cork, the author of an article in that journal. The photograph shows the concentration of phosphorus in the stems of the leaf of a tomato plant. In this case the plant is grown in a solution containing a small amount of P^{32}. Subsequently a leaf was placed in contact with the emulsion of a photographic film which was affected by the beta rays from the radioactive phosphorus.

Firms like Kodak have developed special emulsions for this work, and investigators like Lamerton, Harris and others have made a critical examination of the technique, with particular reference to its sensitivity, resolution and contrast.

15.11. Basic Physics Necessary in Using Isotopes. We summarize below things of importance for the intelligent use of radioactive isotopes.

(*a*) A knowledge of the half-period and disintegration constant. The student should not confuse half-period or half-life with *effective half-life*. This is the time in which the amount of a radioactive substance in the body or in tissue is reduced to one half its initial value because of both radioactive decay and biological removal.

(*b*) A knowledge of the important radiations emitted and their energy values, as listed for a few isotopes in Table XXVII.

(*c*) The meaning of *carrier free*. This is a term used to describe a radioactive specimen in which *all* the atoms are radioactive. Isotopes made by neutron capture, such as P^{32} from P^{31} are of the same chemical nature as the parent atoms and so the active atoms cannot be separated from the inactive. P^{32} prepared by this method is therefore not carrier free.

(*d*) A knowledge of the *specific activity*, or the degree of concentration of the active material. Specific activity is measured by the number of curies or millicuries per gram (sometimes per c.c.) of the whole specimen.

If all the atoms in the specimen are active (as in certain fission products discussed in the next chapter) it is simple and instructive to cal-

culate the maximum possible specific activity. Take iodine ^{131} as an example.

Since the mass of 1 atom of H^1 $= 1{\cdot}66 \times 10^{-24}$ gm

therefore the mass of 1 atom of I^{131} $= 1{\cdot}66 \times 10^{-24} \times 131$

$= 2{\cdot}17 \times 10^{-22}$ gm.

Therefore N, the number of atoms in 1 gm $= \dfrac{1}{2{\cdot}17 \times 10^{-22}}$

$= 4{\cdot}61 \times 10^{21}$.

Now, since the half-period of I^{131} $= 8$ days,

λ, the transformation constant $= \dfrac{0{\cdot}69}{8}$ day^{-1}

$= \dfrac{0{\cdot}69}{8 \times 24 \times 3{,}600}$ sec^{-1}

$= 1{\cdot}00 \times 10^{-6}$ sec^{-1}.

Therefore the number of disintegrations per gm per second $= \lambda N$

$= 1{\cdot}00 \times 10^{-6} \times 4{\cdot}61 \times 10^{21}$

$= 4{\cdot}61 \times 10^{15}$.

But 1 curie $= 3{\cdot}70 \times 10^{10}$ disintegrations per sec.

therefore the number of curies per gm $= \dfrac{4{\cdot}61 \times 10^{15}}{3{\cdot}70 \times 10^{10}}$,

or, the specific activity $= 1{\cdot}24 \times 10^{5}$ curies per gram.

(*e*) The meaning of the *k factor*. In section 12.12 it was stated that when a small source of radium, surrounded by 0·5 mm platinum, is used for gamma ray therapy

dose-rate $= 8{\cdot}3r$ per mg per hr at 1 cm.

This is the value of the *k factor* for radium and hence also for radon per mc. Its value was obtained by experiment, but values of *k* factors in some cases may be calculated with fair accuracy absolutely. We give an example of the method by using Co^{60}.

Absolute calculation of k factor for Co^{60}.

Since 1 mc corresponds to $3{\cdot}70 \times 10^{7}$ disintegrations per second and 1 MeV equals $1{\cdot}59 \times 10^{-6}$ ergs, it follows that, if we deal with 1 mc of any nuclide emitting 1 photon of energy E MeV per disintegration

the total energy radiated per sec $= 3{\cdot}70 \times 10^{7} \times 1{\cdot}59 \times 10^{-6} \times E$ ergs

$= 58{\cdot}8\ E$ ergs.

Hence, if the source is small,

intensity of radiation at r cm from source

$$= \frac{58{\cdot}8\ E}{4\pi r^2}$$

and intensity of radiation at 1 cm from source

$$= \frac{58{\cdot}8\ E}{4\pi}$$

$$= 4{\cdot}68\ E \text{ ergs per cm}^2 \text{ per sec}$$

$$= 1{\cdot}68 \times 10^4 \times E \text{ ergs per cm}^2 \text{ per hr.}$$

If two photons of energies E_1 and E_2 are emitted per disintegration, then

$$\text{intensity at 1 cm} = 1{\cdot}68 \times 10^4\ (E_1 + E_2) \text{ ergs per cm}^2 \text{ per hr.}$$

For cobalt^{60}, where $E_1 = 1{\cdot}17$ MeV and $E_2 = 1{\cdot}33$ MeV,

$$\text{intensity at 1 cm} = 1{\cdot}68 \times 10^4\ (1{\cdot}17 + 1{\cdot}33)$$

$$= 4{\cdot}2 \times 10^4 \text{ ergs per cm}^2 \text{ per hr.}$$

Now the energy flux necessary to give 1 roentgen, as we have shown in section 11.23, depends on the quantum energy of the radiation and may be calculated using absorption coefficients. For both 1·33 MeV and 1·17 MeV, the energy flux per roentgen is approximately 3,000 ergs per cm^2.

Hence for cobalt^{60} the dose rate or

$$\text{the } k \text{ factor} = \frac{4{\cdot}2 \times 10^4}{3{,}000}$$

$$= 14r \text{ per mc per hr at 1 cm.}$$

This result is in fair agreement with the value obtained from experimental measurements given in Table XXVII.

It is important to realize that frequently a photon (or photons) of gamma radiation is not emitted on each disintegration. In such a case, before a k value can be calculated by the above method, a knowledge of the disintegration scheme is necessary. Sometimes these schemes are not simple, but their general nature should be clear from Fig. 15.5, which illustrates the simple scheme for $_{69}$thulium^{170}. This nuclide decays to $_{70}$ytterbium^{170} by the emission of beta particles in two different ways. In the first, the transition is to the ground stable level A of ytterbium without gamma emission. In the second, the emission of a beta ray of somewhat smaller energy than the first, leaves the ytterbium in an excited level B. In the subsequent transition

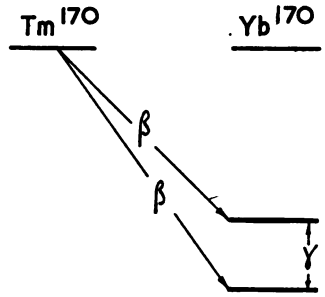


FIG. 15.5. A simple disintegration scheme.—Thulium^{170} decays to ytterbium^{170} by the emission of beta particles to either an excited level B or a ground level A. In the transition from B to A a gamma ray is emitted.

from B to A, a gamma ray is emitted. Since only about $\frac{1}{4}$ (24 per cent) of the total number of disintegrations occur in the second way, the total energy radiated in 1 second by 1 mc of thulium^{170} would be only 24 per cent of the amount given above, that is, of 58·8 E ergs.

As a rule k factors are not calculated absolutely, but from experimental measurements. Thus, by counting beta emission from a sample with a 4π or other suitable counter, the number of disintegrations per second and so the number of millicuries is obtained. From ionization measurements, the dose-rate in r per hour at a specified distance from the sample can be obtained.

The clinical use of isotopes is so widespread that in Britain, through the cooperation of the Atomic Energy Research Establishment, the National Physical Laboratory, the Medical Research Council and the Royal Marsden Hospital, standards of a few isotopes have been and are being prepared. It is now possible to obtain from the N.P.L. sub-standards of iodine^{131} and phosphorus^{32}. Others such as cobalt^{60} and sodium^{24} will soon be available. By comparison with these, specimens in clinical use may be measured using routine methods with counters and ionization chambers.

We conclude this chapter with the solution of a problem illustrating one use of the k factor.

Problem: *Given the half-periods and the k factors of radon and gold*^{198}, *calculate the number of millicuries of gold*^{198} *equivalent to* 1 *millicurie of radon*: (*a*) *if the initial dose-rate of each isotope is to be the same*; (*b*) *if seeds of each are to be left permanently in the site of treatment. Use data given in Table XXVII.*

(*a*) Since the dose-rate for 1 mc radon $= 8{\cdot}3r$ per hr at 1 cm,
and the dose-rate for 1 mc Au^{198} $= 2{\cdot}42r$ per hr at 1 cm,
therefore 1 mc of radon is equivalent to $\frac{8{\cdot}3}{2{\cdot}42}$ or 3·4 mc of Au^{198}.

(*b*) When seeds are left permanently,
the total dose = dose-rate initially × average life.

(See again section 12.14.) Therefore

$$\text{for 1 mc radon, total dose} = 8{\cdot}3 \times \frac{1}{\lambda}$$

$$= \frac{8{\cdot}3 \times 3{\cdot}82 \times 24}{0{\cdot}69}, \text{ if time is in hours,}$$

and for x mc gold^{198}, total dose

$$= \frac{2{\cdot}42 \times 2{\cdot}7 \times 24 \times x}{0{\cdot}69}.$$

But these are equal,

$$\text{therefore} \quad \frac{2{\cdot}42 \times 2{\cdot}7 \times 24}{0{\cdot}69} . x = \frac{8{\cdot}3 \times 3{\cdot}82 \times 24}{0{\cdot}69}$$

$$\text{or } x = 4{\cdot}8 \text{ mc.}$$

PROBLEMS AND QUESTIONS

1. With reference to the equation

$$_{11}Na^{23} + {}_1D^2 = {}_{11}Na^{24} + {}_1H^1,$$

explain (i) what experimental fact this tells you ; (ii) the meaning of the subscript and superscript numbers ; (iii) why $_{11}Na^{24}$ is called radiosodium.

2. Write down the transformation equation when radiosodium is formed by the bombardment of magnesium (atomic weight = 24 ; atomic number = 12) by neutrons.

3. (*a*) When sulphur (atomic weight 32, atomic number 16) is bombarded with nuclei of heavy hydrogen, radiophosphorus (atomic weight 30, atomic number 15) is one of two products. By writing down the transformation equation, show what the other product must be. (*b*) Why is the term radiophosphorus used?

4. $_{15}P^{32}$ and protons are obtained when a certain element is bombarded with neutrons. Find the atomic weight and the atomic number of this element.

5. Discuss as fully as you can the passage of neutrons through matter, describing the various interactions of the neutrons and atoms which may occur. Where possible make specific reference to tissue.

6. (*a*) Radiophosphorus $_{15}P^{32}$ is produced in the following ways, in each of which the bombarding particle is absorbed : (i) sulphur (atomic number 16, mass number 32) is bombarded with neutrons, (ii) chlorine (atomic number 17, mass number 35) is bombarded with neutrons, (iii) phosphorus (atomic number 15, mass number 31) is bombarded with deuterons, (iv) silicon (atomic number 14, mass number 29) is bombarded with alpha particles. Write the equations for these reactions. (*b*) What radiation is emitted by $_{15}P^{32}$, and what is its half-period?

7. (*a*) Explain fully how bombarding alpha particles were used in the experiment which led to the discovery of neutrons. (*b*) Neutrons are sometimes produced by the bombardment of the lithium isotope of mass number 7 by high speed deuterons. Write down the probable transformation equation. (*c*) Explain one method of manufacturing radioactive sodium.

8. Describe several methods for producing neutrons.

9. Work out approximately the number of electron-volts of energy released when a proton and a neutron come together to form a nucleus of heavy hydrogen.

Atomic weight of light hydrogen = 1·0081
Atomic weight of heavy hydrogen = 2·0147
Atomic weight of a neutron = 1·0089

10. How was it proven *by direct experiment* that the nucleus of an atom of heavy hydrogen (the deuteron) consists of a proton and a neutron? How does the sum of the masses of a proton and a neutron compare with the mass of the deuteron?

11. Explain, in a sentence, why neutrons can produce biological effects somewhat similar to X-rays.

12. When an element *A* of atomic weight 45 and atomic number 21 is bombarded with alpha particles a nuclear reaction takes place which liberates protons and a new element B. Find the atomic number and the atomic weight of B.

13. Why can radium E be used as a tracer or indicator when bismuth is used in medical treatment?

14. If a cyclotron can produce protons with energy equal to 20 MeV, what is the energy given by the same set-up to (i) helium nuclei ; (ii) nuclei of heavy hydrogen? Explain your answers.

15. An alpha particle collides with an atom. Describe three possible things which may happen depending on how near it comes to the nucleus of the struck atom.

16. If a minimum of 1·02 MeV is necessary to disintegrate the nucleus of a heavy hydrogen atom, estimate the mass of a neutron.

Mass of ${}_1H^1 = 1{\cdot}00813$; mass of ${}_1D^2 = 2{\cdot}01472$

CHAPTER XVI

URANIUM FISSION AND NUCLEAR REACTORS

16.1. Energy from Destruction of Matter and Nuclear Fission. If man could destroy matter and harness the energy released, the consequences would be amazing. Although 1 million electron-volts are equal to only $1{\cdot}6 \times 10^{-6}$ erg, the number of atoms in even a few milligrams of matter is so enormous that, *if* they all did disappear and change into energy, the results would be startling. If we use the relation $E = mc^2$, we find that for $m = 1$ gram, E is 250 million kilowatt-hours. At once it may be stated that no such disappearance of matter has been observed.

We have seen, however, that when nuclear reactions take place, sometimes there is a loss of mass associated with matter, with an equivalent release of energy. For example, the results of the bombardment of lithium by protons suggest that in this process we may have a useful release of energy. A single 0·3 MeV proton brings about the release of two alpha particles, each with 8·7 MeV, and this looks like a profitable business. The profit, however, is more apparent than real because, for every proton which hits a lithium atom in the right way to cause this reaction, some ten million protons are fired without making any direct hits. Since the energy expended in shooting this large number is entirely wasted, the efficiency of this reaction as a source of power is extremely low.

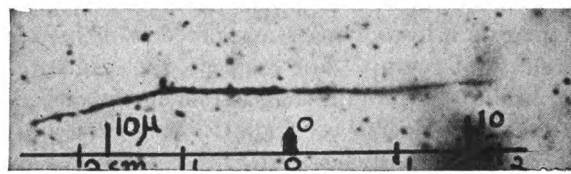
Still another means of obtaining energy from the disappearance of matter is provided by the phenomenon of *fission*, a type of disintegration in which a heavy nucleus, like uranium, after coalescing with a neutron, disintegrates with two particles of comparable size as its major products.

More than one country shared in the honour of the discovery of fission. In 1938, Hahn and Strassmann in Germany, following up work done by Curie and Savitch in France, found that a group of the radioactive bodies which resulted from the bombardment of uranium by neutrons were chemically similar to the element barium. They eventually concluded that barium was a product of the uranium-neutron interaction. Now the formation of an element, such as

barium, which occurs in the middle range of the periodic table, as a result of the union of a very heavy element like uranium with a neutron, was such a new and unexpected phenomenon that it was startling. But there was no doubt about the matter.

Later, Meitner, when working at the Physical Institute, Academy of Sciences, Stockholm, and Frisch, of the Institute of Theoretical Physics, Copenhagen, came to the conclusion that " the uranium nucleus has only small stability of form and may, after neutron capture, divide itself into two nuclei of roughly equal size ". They proposed the name " fission " to describe the phenomenon and predicted that " these two nuclei will repel each other and should gain a total kinetic energy of about 200 million electron-volts ". This picture of fission was soon well established.

A beautiful illustration of the phenomenon is given in Fig. 16.1, the reproduction of a photograph taken by Professor Pierre Demers of the University of Montreal. This photograph shows the tracks of the two heavy fragments resulting from the fission of U^{235} and was



Courtesy Professor Pierre Demers

FIG. 16.1. Enlargement showing the tracks of the two heavy fragments resulting from the fission of uranium 235 by a neutron.

obtained by using the photographic emulsion method. The origin, where fission takes place, is marked by the short blank gap opposite the zero mark on the accompanying scale. The heavy tracks on either side of the zero mark the paths of the heavy fission fragments. To quote Dr. Demers, " the track at the left is longer and denser than the other one which dipped out of focus. It shows one bend after a collision with a nucleus, probably of silver or of bromine, which travelled some distance and left that other short dense track going up. Occasional slight bending is visible at other points along the two fission tracks."

From the standpoint of the useful release of energy and possible development of power, uranium fission is of importance for two reasons : (1) the large amount, approximately 200 MeV, of energy released per single fission ; and (2) the possibility of a chain reaction.

It is not difficult to estimate the amount of energy released per fission. For elements whose atomic weights are midway between those of very light elements like hydrogen and helium and the very heavy elements like radium and uranium, *the mass per particle* (neutron or proton) *in the nucleus is less than for either the light or heavy elements.* A concrete example should make the point clear. The exact atomic mass of uranium^{235} is 235·12, hence the *average* mass per neutron or proton in the nucleus is slightly *greater* than 1. Now consider the element barium^{138}. Since its atomic mass is 137·916, the average mass of its 138 neutrons and protons is slightly *less* than 1. The same may be said of lanthanum^{139}, another element which appears as a fission product, with an atomic mass of 138·955. When, therefore, a heavy nucleus such as U^{235} gives rise on disintegration to products of intermediate weight like Ba and La, there is a loss of mass associated with matter and hence a gain of energy. Remembering the conversion relation, 0·0011 of an atomic mass unit is equal to 1 MeV, the reader can show from the above numbers that approximately 200 MeV are released per fission.

As already indicated, in terms of kilowatt-hours 200 MeV is an extremely small amount of energy. But if a sufficiently large number of atoms undergo fission, the resultant release of energy can be very large. For example, the destruction by fission of 1 pound of uranium would give about 11 million kilowatt-hours. It is perhaps more striking to state that the energy released in fission per atom is 40 million times the amount released per atom in the burning of coal.

16.2. The Chain Reaction. The second reason why fission is so important from the energy standpoint is due to the fact that in addition to the two heavy fragments, the products of disintegration include one or more neutrons. Thus, *fission is caused by neutrons, and neutrons are emitted in the process.* It is therefore possible that, once fission is started, these emitted neutrons, or some of them, can cause further fission, with further emission of more neutrons, thus giving a chain reaction with liberation of energy continuing as long as the disintegrating chain goes on. If the energy is liberated at an extremely rapid rate, a bomb may result; if, however, the rate is slow and controlled, the energy released may be used as a new source of power.

What, then, are the possibilities of establishing such a chain reaction, and, if established, how can it be controlled so that, once started, it does not run amok like a fire in a dry forest? The answers to these questions were provided during the years of World War II,

in work of such importance that we are sometimes said to live in a new age, designated by the much abused word atomic. As this work has far-reaching consequences in radiology, we shall examine somewhat carefully the conditions necessary to establish a chain reaction.

In a single fission of U^{235} on the average 2·5 neutrons are emitted. Suppose that the average number is 2 and that each liberated neutron is able to bring about further fission. It is easy to see that the total number of neutrons would rapidly increase, being 2 after the first generation, then 4 or 2^2, then 8 or 2^3, and so on until in a short time the number is very large. When an atomic bomb explodes, this rapid chain increase actually takes place, but, with ordinary masses of even purified uranium there is no such chain reaction for several reasons. (*a*) The element uranium consists of about 99·3 per cent of U^{238}, 0·7 per cent of U^{235}, and such a small fraction of U^{234} that in our discussion it may be neglected. Now U^{235} undergoes fission much more readily than U^{238}. To be more exact, fission of U^{235} is brought about by neutrons of any speed, very slow thermal neutrons (with energy of the order of 0·025 eV) being most effective of all. On the other hand, although neutrons possessing more than 1 MeV of energy cause fission in U^{238}, those with energy less than that amount do not do so. Since the average kinetic energy of neutrons liberated by fission is a little less than 1 MeV, fission of U^{238} is decidedly small. (*b*) These fast neutrons, with energy a little less than 1 MeV, on striking nuclei of atoms of U^{238} bounce off losing only a little energy at each collison (because the mass of U^{238} is so much greater than that of a neutron). They, therefore, keep bouncing about, most of them making many collisions and so being gradually slowed down, until they are all accounted for by the following processes. (i) A few hit the relatively small number of U^{235} nuclei, causing fission. (ii) Some escape altogether from the mass of uranium in which they were originally generated. (iii) Some have been slowed down enough to be *captured* by U^{238}, without resulting fission. This capture is a very important process *which takes place with a high degree of probability for neutrons with energy about* 38 *electron-volts.* (iv) If the uranium contains impurities, many neutrons are captured by their atoms.

We see, therefore, that if a certain number of neutrons are present at any instant in a given mass of uranium, as time goes on there will be a *gain* in the number because of fission of U^{235} (2·5 being liberated per fission), and a *loss* due to escape and to capture by U^{238} and by impurities. *If the losses exceed the gains, the number of neutrons will steadily decrease, and a chain reaction is not possible.* Actually, none is

set up in ordinary uranium. To establish a chain reaction, as is done in *atomic piles* or *nuclear reactors*, the practical problem is (*a*) to make the gains just exceed the losses and (*b*) to devise a control by means of which the process can be started or stopped.

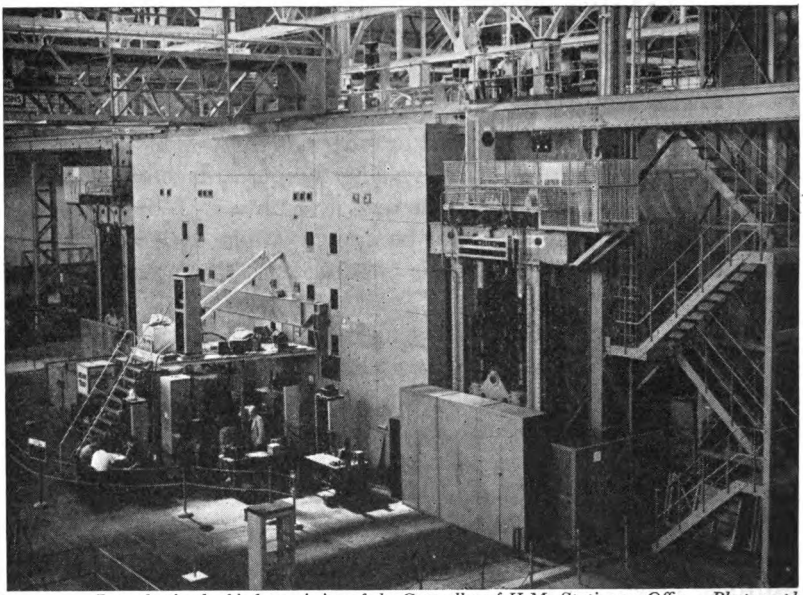
Gains can be increased by increasing the percentage of U^{235}, that is, by *enriching* the pile, to use the technical phrase. With a mass of ordinary uranium, this need not be done, because by certain means immediately to be explained, it is possible both to increase the gain and decrease the loss.

Loss due to escape can be lessened by increasing the size of the mass of uranium. This is because escape of neutrons depends on the area of the surrounding *surface*, whereas production depends on the *volume* of the material. Since the area of a sphere, to take a specific example, depends on the square of its radius and its volume on the cube, it should be evident that doubling the radius will increase the surface area four times, but the volume eight times, since $2^2=4$ and $2^3=8$. Consequently, as a unit is made larger and larger, escape of neutrons, depending on the surface area, becomes *relatively* less important than production, which depends on the volume. When scientists were first seeking to establish a chain reaction, one of their first problems was to estimate how large a unit would be necessary to offset the loss by escape. Escape is also lessened by the reflection of neutrons back from the outer casing of a reactor, especially from a substance like carbon.

Loss due to capture is decreased by purifying the uranium, removing impurities which capture neutrons.

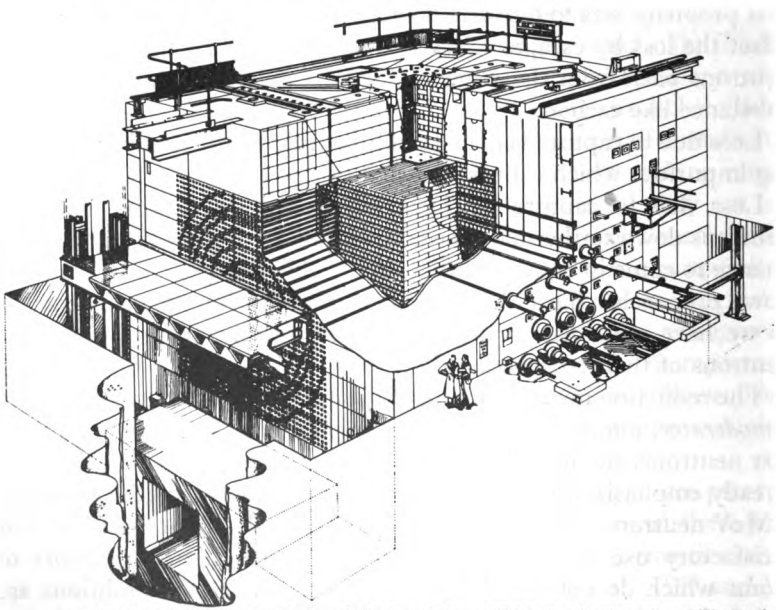
Loss due to capture by U^{238} is reduced by slowing liberated neutrons down to thermal speeds before they (or most of them) get a chance to come in contact with atoms of this isotope. This slowing-down process has the added advantage of increasing the gain because, as we have seen, fission of U^{235} is most readily brought about by neutrons of thermal speeds.

The reduction in speed is brought about by the use of what is called a *moderator*, a material consisting of *light* atoms which, when hit by fast neutrons, rapidly slows them down. (In section 14.7, we have already emphasized that after some twenty collisions with protons, a 5 MeV neutron is slowed until its energy is only about 0·1 eV.) For satisfactory use as a moderator, a substance must also consist of atoms which do not readily capture neutrons. Both conditions are satisfied by purified graphite, by beryllia or beryllium, and by heavy water. Note that the cross-section (absorption coefficient) for



Reproduction by kind permission of the Controller of H.M. Stationery Office. Photograph Crown copyright

FIG. 16.2. A view of B E P O, a Harwell Nuclear Reactor.



Reproduction by kind permission of the Controller of H.M. Stationery Office. Illustration Crown copyright

FIG. 16.3. A part sectional view of B E P O.

thermal neutrons is 0·0006 for deuterium, 0·0035 for beryllium and 0·0048 for carbon. Compare these values with 2·5 for iron, 700 for boron and 2,500 for cadmium.

In a chain-reacting pile (or nuclear reactor) of the thermal nuclear type, a large number of purified uranium rods, encased in sheaths of aluminium, are interspersed in a large mass of moderator so that neutrons liberated in any one rod are slowed down before they strike a neighbouring one. In BEPO, one of the Harwell reactors, 200 cylindrical uranium rods, each 12 in × 9/10 in, are inserted in each of 900 channels in the central part of a cube of graphite 26 × 26 × 26 ft. This " core " is surrounded by an outer casing of reinforced concrete, 7 ft 6 in thick, lined with 6 in cast iron plates. Some idea of the construction and the general appearance of this reactor can be had from Fig. 16.2 and Fig. 16.3, reproduced through the kind permission of the Controller of H.M. Stationery Office.

This book is not the place to give the details of the construction of actual piles, which may be operated at power levels as low as a few watts or as high as some hundred thousand kilowatts, but our description of basic principles would not be complete without an explanation of the means of starting or stopping a pile. Control is possible because, as we have seen above, a few substances, notably cadmium and boron, absorb slow neutrons to an exceptionally high degree. Accordingly, a pile is designed so that rods or plates of a material like steel, coated with cadmium or boron, can be inserted to varying degrees inside it. Suppose a pile has been designed to operate at a certain power level with a cadmium control half-way in. Then, with the rod or rods pushed all the way in, no chain reaction is possible because too many neutrons are captured by the cadmium. On gradually pulling out the rods, cadmium capture becomes less and less and at a certain stage the reaction begins. If the controls are pulled too far out, the reaction will proceed too vigorously, and care must always be exercised to guard against this. When a reactor is started, the control rods are set in such a position that the chain reaction takes place, the power developed steadily increasing. When the power level desired is reached, the controls are then set in such a position that the power is held at that level. At this stage, that is, when the reactor is running steadily, 1 neutron per fission is used to maintain the chain reaction.

Since no special source of neutrons (apart from the fissionable material) is placed within a reactor, the reader may wonder how the chain process is started. This is because a few stray neutrons from

cosmic rays are always present in the atmosphere and, moreover, because there is always the off-chance of a spontaneous fission.

16.3. Reactors and Radiology. In this book we are not concerned with the different types of reactors which have been and are being constructed, nor with their use as a source of power. But we are greatly concerned with their significance in radiology and make reference to the following applications.

(*a*) In one of the Harwell reactors there is a heavy roof which may be moved to one side thus permitting the direct irradiation by neutrons of small animals like mice. Alternately a layer of metal may be placed below the animals, who are then subjected to the gamma radiation emitted by the metal because of neutron capture.

It is possible that in the future reactors may be built designed especially for biological investigation.

(*b*) The outstanding use of a reactor is for the production of radioactive isotopes. There are two main methods: (i) by the introduction of stable materials into the pile where they are subjected to intense neutron beams; (ii) by chemical extraction from the fission products.

(i) When a substance like Co^{59} is put within a reactor, neutron capture takes place and Co^{60} begins to be manufactured at a rate which is constant, provided the neutron flux remains constant. Now as soon as any active material like Co^{60} is present, it begins to decay and we have essentially the same situation as when radon is manufactured from long-lived radium. If the substance is left long enough in the reactor, an equilibrium amount, I_0 we shall designate it, of the active material is reached when the rate of production equals the rate of decay. Hence, as with radon, the law of growth of the active substance is

$$I = I_0(1 - e^{-\lambda t}),$$

where I is the amount present after a time t.

It follows at once that 50 *per cent of the equilibrium or maximum amount is produced in a time equal to the half-period.* For Co^{60} this is 5·3 years, for Na^{24} 14·5 hours, and so on.

Using the above law of growth, the student should be able to work out that: (*a*) 10 per cent of the maximum amount is obtained in a time $0{\cdot}153T$, where T is the half-period; (*b*) 90 per cent in a time $3{\cdot}33T$. He should also be able to solve the following problem.

Problem: *If* 20 *mc* of P^{32} *are produced in a reactor in* 10 *days, find*: (*a*) *the maximum amount obtainable*; (*b*) *the amount produced in* 3 *weeks. Take the half-period of* P^{32} *as* 14 *days.* Ans. (*a*) 29·5 mc, (*b*) 26·5 mc.

Calculation of the specific activity of an isotope obtained by neutron capture in a reactor.

Consider a slab of stable material 1 cm² in sectional area on which a flux of n neutrons per second is incident.

Let σ = the cross-section of the material for neutron absorption and N = the *total* number of atoms per c.c. in the slab.

Then it follows, exactly as shown in section 10.19, that

the number of active atoms produced per c.c. per sec $= N\sigma n$,

or the number of active atoms produced per gram per sec $= \dfrac{N\sigma n}{\rho}$

where ρ is the density of the material (in grams per c.c.).

Now, since the mass of 1 atom of hydrogen $= 1{\cdot}66 \times 10^{-24}$ gm, the mass of 1 atom of an element of atomic weight M

$$= 1{\cdot}66 \times 10^{-24} \times M.$$

Therefore the number of atoms of the element in 1 gram

$$= \frac{1}{1{\cdot}66 \times 10^{-24} \times M},$$

and hence N, the number of atoms in 1 c.c. $= \dfrac{\rho}{1{\cdot}66 \times 10^{-24} \times M}$.

Therefore, the number of *active* atoms produced per gram per sec, which we have seen

$$= \frac{N\sigma n}{\rho}$$

$$= \frac{\rho}{1{\cdot}66 \times 10^{-24} \times M} \cdot \frac{\sigma n}{\rho}$$

$$= 6{\cdot}02 \times 10^{23} \times \frac{\sigma n}{M}.$$

If we take Co^{60} as an example, we have $M = 60$, $\sigma = 22{\cdot}5 \times 10^{-24}$, and we obtain, substituting in the above, the number of active atoms of Co^{60} per gm per sec $= 0{\cdot}226n$. The value of n depends on the reactor. If we take $n = 10^{12}$ (which applies to the pile BEPO at Harwell), we obtain

the number of active atoms of Co^{60} per gm per sec $= 2{\cdot}26 \times 10^{11}$.

At equilibrium, this is also the number of disintegrations per second, therefore, since 1 curie $= 3{\cdot}70 \times 10^{10}$ disintegrations per sec, the specific activity of Co^{60} *at equilbrium* $= \dfrac{2{\cdot}26 \times 10^{11}}{3{\cdot}70 \times 10^{10}}$

$= 6{\cdot}1$ curie per gram.

To obtain such a specific activity Co^{59} would have to be left in the reactor for 25 years or more, but, as we have seen, 10 per cent or 610 mc per gram can be obtained in a time $0{\cdot}153T$ or in 9·7 months.

(ii) *Fission products.*

The original products of fission (apart from neutrons) are highly radioactive and in their transformation to stable elements more active elements are formed. $Xenon^{139}$, one of many fission products, decays to the stable isotope lanthanum after the following transformations.

$$_{54}Xe^{139} = {}_{55}Cs^{139} + \beta,$$
$$_{55}Cs^{139} = {}_{56}Ba^{139} + \beta,$$
$$_{56}Ba^{139} = {}_{57}La^{139} + \beta.$$

It is not surprising, therefore, that when a reactor has been in operation for some time, almost colossal amounts of radioactive elements have accumulated. The separation of some of these by chemical means provides the second main source of isotopes and is an important part of the work of the Chemistry and Isotope Divisions at Harwell. To give one example quoted by Sir John Cockcroft—"The Radiochemical Centre has developed a small plant for extracting tens of curies of radiocaesium from the fission product wastes."

In section 15.11 an example of the method of evaluating the specific activity of a fission product has been given.

16.4. Much of the work discussed in this book provides ample evidence that in this so-called atomic age—a period which began long before the discovery of nuclear fission—the work of the physicist has been outstanding. To some, he has been the villain responsible for such diabolic devices as atom and hydrogen bombs; to others he is the magician who waves a magic wand and produces a new source of energy as well as isotopes of great benefit to mankind. Our interest has been chiefly in the applications of his discoveries in medicine. In the past great advances have been made in this field and it is safe to predict that the future will bring many more new applications. Of these the student need have no fear if he has acquired a grasp of basic principles. Applications sometimes change overnight, fundamental principles are eternal. So in concluding this book the author commends to students of all ages the following words of A. N. Whitehead, mathematician and philosopher, "The details of knowledge which are important will be picked up *ad hoc* in each avocation of life, but the habit of the active utilisation of well understood principles is the final possession of wisdom."

APPENDIX A

PROTECTION

A MENACE to health which is invisible and cannot be touched is a much more insidious danger than one which can be seen and felt. In the early days of X-rays, this somewhat obvious truth was driven home in tragic ways, because some of the pioneer workers paid with their lives for their ignorance of the harmful effects of penetrating radiations. Today in hospitals and other centres where X- and other radiations are being used, protective measures are a matter of routine concern. But so complicated are the biological actions of such radiations that information is by no means complete both concerning long-term effects and the maximum permissible amounts to which a person may be subjected. The use of high voltage machines for the generation of ultra-penetrating rays, the widespread use of radioactive isotopes, and research and development work relating to atomic energy have greatly increased the number of people who are habitually exposed to radiations. The building in the near future of nuclear power installations with the resulting accumulation of vast products of associated radioactive materials* will still further increase the magnitude of the problem of protection. To some extent whole populations will be effected. Indeed, to a slight extent, this aspect is already with us, as will be evident from the following statement taken from an address by Sir Rock Carling. " It is well known that a single bomb detonated in Nevada in favourable meteorological conditions can produce a fall-out in the catchment area of the Thames Valley that raises, for a few hours, the radiation level of the river above that laid down by the authorities."

It is not surprising, therefore, that in both national and international committees much time has been devoted to the problem of protection by outstanding leaders in radiology. As a result of action taken in 1950 by the International Commission on Radiological Protection (I.C.R.P.), studies in the various specialized fields were undertaken by six special international sub-committees. A summary

* " Even at the present moment . . . there would be a possibility of setting up a commercial unit to utilise, not a thousand, or a hundred thousand—but a million curies of such products." From an address given by Sir Rock Carling, at the Sixteenth Annual Congress of the British Institute of Radiology, November 23, 1954.

of some of their recommendations has been published in the April 1954 issue of the *British Journal of Radiology*, and the final report will be published in full in the same journal in the early summer of 1955, as Supplement No. 6.

The complete report is so long and so detailed that in this book reference is made to only a few important points. The author has quoted freely from the summarized report as well as from the complete recommendations, a pre-publication copy of which was kindly given him by Mr. W. Binks, Secretary of the Commission, and Director of the Radiological Protection Service of the Medical Research Council and the Ministry of Health of Great Britain. Use has also been made of data given in Handbook 55 of the U.S. National Bureau of Standards on *Protection against Betatron-Synchrotron Radiations up to* 100 *MeV*.

1. Permissible Dose for External Radiation

(*a*) " Permissible dose is defined as that dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime."

(*b*) For whole body exposure to X- and γ-radiation the following amounts are considered to be well below the limit indicated in the above definition. For blood-forming organs, gonads, and eyes, permissible dose is 0·3*r* per week ; for the skin, 0·6*r* per week.

(*c*) If the rad is used instead of the roentgen, the report considers it is of sufficient accuracy to use the same numerical values, that is 0·3 rad and 0·6 rad. (Recall that 1 rad = 100 ergs per gram and that 1*r* = 93 ergs per gram of tissue.)

(*d*) These numbers do not apply to all types of ionizing radiations, because the biological effectiveness of a radiation depends on its specific ionization. For X-rays up to 250 kV a mean value is 100 ion pairs per micron of water (or soft tissue). When we deal with heavy ionizing particles such as protons, neutrons, and alpha rays, values of specific ionization can be as high as several 1,000 ion pairs per micron. A given dose in ergs per gram of such radiations is biologically more effective than the same dose for smaller specific ionizations. For that reason, the term *relative biological effectiveness* (r.b.e.) has been adopted. This is the number of times a particular radiation is biologically more effective than " that of X-radiation with an average specific ionization of 100 ion pairs per micron of water ",* whose

* The N.B.S. Handbook, No. 55, uses as the standard of r.b.e. gamma rays from radium filtered by 0·5 mm of platinum, but there is no essential difference between the two. Whichever is chosen as a standard, the other has an r.b.e. of 1.

r.b.e. is taken as 1. " For practical purposes, an r.b.e. of 10 is applicable to fast neutrons and protons up to 10 MeV and an r.b.e. of 20 to heavy recoil nuclei, for whole body radiation and the most sensitive critical organs." (See also Table XXVIII below.)

(*e*) *The Rem.* Because of this dependence of biological effectiveness on both the dose in ergs per gram and the r.b.e., the commission has recommended a new unit, the *rem*, which, however, although used in their report, has not yet been officially adopted.

" The rem is the absorbed dose of any ionizing radiation which has the same biological effectiveness as one rad of X-radiation with average specific ionization of 100 pairs per micron of water, in terms of its air equivalent, in the same region." Hence

$$\text{dose in rems} = \text{dose in rads} \times \text{r.b.e.}$$

Table XXVIII, based on data in both the commission's report and in the N.B.S. Handbook, will perhaps help to make the use of the rem clearer.

TABLE XXVIII

BASIC PERMISSIBLE DOSE FOR BLOOD-FORMING ORGANS, GONADS AND EYES

Radiation	R.B.E.	Rems	Rads or Roentgens
X-rays, 0·1 to 100 MeV -	1	0·3	0·3
Electrons, 0·1 to 100 MeV -	1	0·3	0·3
Protons up to 10 MeV - -	10	0·3	0·03
Neutrons, thermal to 10 MeV	10	0·3	0·03
Alpha rays and heavy recoil -	10 to 20	0·3	0·03 to 0·06

For skin, all rem and rad values are doubled.

For neutrons, permissible levels are sometimes also expressed in terms of neutron flux densities. Values drop from 2,000 neutrons per cm^2 per sec for thermal, to 30 for fast neutrons in the range 3 to 10 MeV.

2. Permissible Dose for Internal Radiation. A considerable part of the report of the commission is devoted to this topic, which, in these days of widespread use of active isotopes is of great importance, although far from simple. Since, as we have seen in Chapter XV, certain elements are selectively absorbed by particular organs, the amount of material which may safely be ingested or inhaled depends markedly on the element under consideration. No attempt is

made to summarize this part of the report, which includes not only recommendations but valuable data about isotopes. We merely quote a few sentences from the summary in *The British Journal of Radiology*.

" An assessment has been made of the values of maximum body burden and maximum concentrations in air and water of 96 radioisotopes that are considered permissible for occupational exposure.

" Only in the case of radium is there an accumulation of human experience over a period of years that is suitable as a basis of selection of the maximum permissible levels.

" Following accepted practice in the industrial and public health field, it is recommended that, in the case of prolonged exposure of a large population, the permissible level for radioactive isotopes accepted for occupational exposure be reduced by a factor of 10.

3. Protective Barriers. As is to be expected, the report gives detailed information about the necessary thicknesses of protective barriers for a wide range of X-rays, as well as the lead equivalent of such protective materials as concrete, iron, brick, lead-glass and lead rubber.

4. Monitoring and Protection of Personnel. Practical means for providing adequate protection include (*a*) monitoring of laboratories, wards and all places where ionizing radiations may be present; and (*b*) methods of finding out the weekly doses to which personnel are exposed.

Protection of personnel is provided in two ways: (*a*) by the use of small ionization chambers; and (*b*) by the use of film badges, one of which should be carried or worn continuously by each person exposed to radiation. The principle of the small ionization chamber has already been explained in section 11.11. It should be added, however, that a " pocket " chamber, called the fountain-pen monitor, which incorporates its own electrometer (a gold plated quartz fibre electroscope) is now available.

A film badge consists of a piece of photographic film mounted in a holder which usually also contains a thin metal filter. The principle is extremely simple. Radiation incident on the badge causes a blackening of the film, the density of the developed image increasing with the amount of exposure. Corresponding doses, usually after a period of one week, are obtained from calibration curves for any particular type of film. The chief difficulty involved in their use is the fact that the density obtained for the same dose depends markedly on the quality of the radiation. To quote Spiegler, an authority in

this field, " the (Ilford) PM-1 film requires about 60 mr in the low voltage (diagnostic) region to attain density 1, about 360 mr at 400 kV, and over 700 mr in the 1 MeV region and above." Stated otherwise and again we quote Spiegler, with a certain film, " with gamma rays density 1 obtained in any one week signifies more than twice the tolerance dose. . . . In the diagnostic region and with rays scattered from 200–250 kV plants density 1 indicates approximately a fifth of the tolerance dose." (In passing it is noted that Spiegler has shown that, because of the variation in electron emission from metal foils with wave length, the blackening of films can be used to measure *quality*.)

The construction of filters in actual use varies somewhat. At the Royal Marsden Hospital, routine protection is carried out using a holder designed by Turner. " This consists of a metal carrier, clipped to the breast pocket and holding the film, which is screened by 1·5 mm of brass, the brass having in its centre a 1 cm diameter circular aperture." In a badge used at Harwell, the film is covered in part by a special lead screen, X- and gamma rays affecting the emulsion under the screen, beta rays elsewhere. In a second type used at Harwell, cadmium replaces lead. This type " normally incorporates filter inserts of 0·04 in of cadmium inside a tinned steel case approximately 0·015 in thick, which is also painted ". The presence of cadmium makes this holder valuable in places where slow neutrons are present and, moreover, " the cadmium filter has been designed to even out the response of PM-1 film from about 130 kV upwards ".

The above quotations are from a short article by Stephenson in the *British Journal of Radiology* on " Filters for Health Film Holders ". In this article the author gives experimental data to show that " in medical radiology a film holder of the Harwell type should contain, inside the steel case, tin filter inserts of thickness not less than 0·03 in and not greater than 0·05 in. Such holders would also be somewhat cheaper than the ones with cadmium filters."

APPENDIX B

SOME USEFUL CONSTANTS AND CONVERSION FACTORS

1 coulomb	$=3 \times 10^{9}$ statcoulombs
300 volts	$=1$ statvolt
1 farad	$=9 \times 10^{11}$ statfarads
1 microfarad	$=9 \times 10^{5}$ statfarads
1 angstrom	$=10^{-8}$ cm
1 micron	$=10^{-3}$ mm
1 millimicron	$=10^{-6}$ mm
1 X unit	$=10^{-3}$ angstrom
1 electron-volt	$=1{\cdot}6 \times 10^{-12}$ erg
1 electronic unit of charge	$=1{\cdot}60 \times 10^{-19}$ coulomb $=4{\cdot}80 \times 10^{-10}$ statcoulomb
$\frac{\text{charge on electron}}{\text{mass of electron}}$	$=1{\cdot}76 \times 10^{8}$ coulomb per gram
mass of a hydrogen atom	$=1{\cdot}67 \times 10^{-24}$ gram
mass of an electron	$=9{\cdot}11 \times 10^{-28}$ gram
charge carried by 1·008 gm. of hydrogen	$=96490$ coulomb
Planck's constant (h)	$=6{\cdot}62 \times 10^{-27}$ erg $\times$ sec.
shortest wave length	$=\frac{12{\cdot}4 \times 10^{3}}{\text{maximum voltage}}$ angstroms
Avogadro's number	$=6{\cdot}06 \times 10^{23}$

APPENDIX C

TABLE XXIX

ATOMIC NUMBERS, ATOMIC WEIGHTS AND STABLE ISOTOPES

Element	Symbol	Atomic Number	Atomic Weight	Mass Number of Isotopes
Hydrogen	H	1	1·0081	1, 2
Deuterium	D	1	2·0147	
Helium	He	2	4·0039	3, 4
Lithium	Li	3	6·940	6, 7
Beryllium	Be	4	9·02	9
Boron	B	5	10·82	10, 11
Carbon	C	6	12·010	12, 13
Nitrogen	N	7	14·008	14, 15
Oxygen	O	8	16·0000	16, 17, 18
Fluorine	F	9	19·00	19
Neon	Ne	10	20·183	20, 21, 22
Sodium	Na	11	22·997	23
Magnesium	Mg	12	24·32	24, 25, 26
Aluminium	Al	13	26·97	27
Silicon	Si	14	28·06	28, 29, 30
Phosphorus	P	15	30·98	31
Sulphur	S	16	32·06	32, 33, 34, 36
Chlorine	Cl	17	35·457	35, 37
Argon	A	18	39·944	36, 38, 40
Potassium	K	19	39·096	39, 40, 41
Calcium	Ca	20	40·08	40, 42, 43, 44, 46, 48
Scandium	Sc	21	45·10	45
Titanium	Ti	22	47·90	46, 47, 48, 49, 50
Vanadium	V	23	50·95	51
Chromium	Cr	24	52·01	50, 52, 53, 54
Manganese	Mn	25	54·93	55
Iron	Fe	26	55·84	54, 56, 57, 58
Cobalt	Co	27	58·94	59
Nickel	Ni	28	58·69	58, 60, 61, 62, 64
Copper	Cu	29	63·542	63, 65
Zinc	Zn	30	65·38	64, 66, 67, 68, 70
Gallium	Ga	31	69·72	69, 71
Germanium	Ge	32	72·60	70, 72, 73, 74, 76
Arsenic	As	33	74·91	75
Selenium	Se	34	78·96	74, 76, 77, 78, 80, 82
Bromine	Br	35	79·916	79, 81
Krypton	Kr	36	83·7	78, 80, 82, 83, 84, 86
Rubidium	Rb	37	85·48	85, 87
Strontium	Sr	38	87·63	84, 86, 87, 88
Yttrium	Y	39	88·92	89
Zirconium	Zr	40	91·22	90, 91, 92, 94, 96
Molybdenum	Mo	42	95·95	92, 94, 95, 96, 97, 98, 100
Ruthenium	Ru	44	101·7	96, 98, 99, 100, 101, 102, 104
Rhodium	Rh	45	102·91	103
Palladium	Pd	46	106·7	102, 104, 105, 106, 108, 110

Element	Symbol	Atomic Number	Atomic Weight	Mass Number of Isotopes
Silver	Ag	47	107·880	107, 109
Cadmium	Cd	48	112·41	106, 108, 110, 111, 112, 113, 114, 116
Indium	In	49	114·76	113, 115
Tin	Sn	50	118·70	112, 114, 115, 116, 117, 118, 119, 120, 122, 124
Antimony	Sb	51	121·76	121, 123
Tellurium	Te	52	127·64	120, 122, 123, 124, 125, 126, 128, 130
Iodine	I	53	126·92	127
Xenon	Xe	54	131·3	124, 126, 128, 129, 130, 131, 132, 134, 136
Caesium	Cs	55	132·91	133
Barium	Ba	56	137·36	130, 132, 134, 135, 136, 137, 138
Lanthanum	La	57	138·92	138, 139
Cerium	Ce	58	140·13	136, 138, 140, 142
Praseodymium	Pr	59	140·92	141
Neodymium	Nd	60	144·27	142, 143, 144, 145, 146, 148, 150
Samarium	Sm	62	150·43	144, 147, 148, 149, 150, 152, 154
Europium	Eu	63	152·0	151, 153
Gadolinium	Gd	64	156·9	152, 154, 155, 156, 157, 158, 160
Terbium	Tb	65	159·2	159
Dysprosium	Dy	66	162·46	156, 158, 160, 161, 162, 163, 164
Holmium	Ho	67	164·935	165
Erbium	Er	68	167·2	162, 164, 166, 167, 168, 170
Thulium	Tm	69	169·4	169
Ytterbium	Yb	70	173·04	168, 170, 171, 172, 173, 174, 176
Lutecium	Lu	71	175·0	175, 176
Hafnium	Hf	72	178·6	174, 176, 177, 178, 179, 180
Tantalum	Ta	73	180·88	181
Tungsten	W	74	183·88	180, 182, 183, 184, 186
Rhenium	Re	75	186·31	185, 187
Osmium	Os	76	190·2	184, 186, 187, 188, 189, 190, 192
Iridium	Ir	77	193·1	191, 193
Platinum	Pt	78	195·23	192, 194, 195, 196, 198
Gold	Au	79	197·2	197
Mercury	Hg	80	200·61	196, 198, 199, 200, 201, 202, 204
Thallium	Tl	81	204·39	203, 205
Lead	Pb	82	207·21	204, 206, 207, 208
Bismuth	Bi	83	209·00	209
Uranium	U	92	238·07	234, 235, 238

INDEX

Absorption :
  and atomic number, 167
  apparent, 156
  coefficients, 162, 164, 166, 168
  critical wave lengths, 157, 160
  nature of, 156
  of alpha rays, 214
  of beta rays, 215
  of gamma rays, 216
  of X-rays, 114, 118, 150
  true, 156
A.c., 3
Accelerator, linear, 259, 270, 278
Active deposit, 237
Activity, specific, 297, 298, 311
Air dose, 195
Air wall chamber, 191
Allison, 157, 168
Alpha rays, 211
  artificial, 275
  bombardment by, 243, 273, 275
  collisions, 243
  counting, 213
  scattering of, 212, 243
  tracks, 212
Alternating currents, 1, 3
  average value, 7
  frequency of, 4
  power factor, 16
  r.m.s. value, 6
  strength of, 5
Amplification factor, 102
Amplifier, 102
Anderson, 284
Angstrom, 105
Anode :
  massive, 72
  of X-ray tube, 72
  rotating, 79, 80
Astatine^{211}, 293
Aston, 57, 58
Atlee, 70, 71, 194
Atom :
  nucleus of, 46, 242
  structure of, 45
Atomic :
  absorption coefficient, 168, 169
  pile, 307, 309
  reactor, 307, 309
  stopping power, 214
Atomic number, 46, 59, 239, 319
  and absorption, 167
  and wave length, 132
  table of, 319
Atomic weight, 46, 59
  table of, 239, 319
Auger electrons, 218
Auto-radiography, 296
Auto-transformer, 31
Average life, 234

Back scatter, 195
Bainbridge, 57
Baldwin, 83
Becker, 276
Becquerel, 210
Belcher, 226
Beryllium window, 85, 110, 145
Beta rays, 214
  primary, 215, 218
  secondary, 217, 218
  therapy, 293
  tracks, 215
Betatron, 49, 259, 266
Bias, grid, 101
Binks, 314
Biological effect :
  of X-rays, 110
  r.b.e., 314
Birge, 60
Blackett, 284
Bohr, 134
Bombardment by :
  alpha particles, 243, 273, 275
  cathode rays, 48
  deuterons, 275
  gamma photons, 280
  neutrons, 279
  nuclei, 273
  protons, 274
Bothe, 276
Bouwers, 115
Bragg, 125
Bremsstrahlung rays, 130
Brickwedde, 60
Brush discharge, 27

Bucky, 172
Bucky diaphragm, 172
Bull, 292

Calorimeter and energy, 203
Calutron, 62
Canal rays, 54
Capacitive reactance, 11
Capture, neutron, 279
Carling, 313
Cascade generator, 250
Cathode-ray oscilloscope, 49
Cathode rays, 36, 40, 42, 44
Cathode, shielded, 72
Centrifuge, 64
Cerium^{144}, 293
Chadwick, 276, 289
Chain reaction, 305, 309
Chamberlain, 119
Chambers :
  air wall, 191
  extrapolation, 196
  free air, 191
  ionization, 180, 181, 190, 191, 194, 315
  mesh, 194
  standard, 180, 181, 187
  thimble, 181, 190
  walls, 194
Characteristic curves :
  diode, 90
  photo-image, 142
  triode, 101
Characteristic X-rays, 129, 131, 150, 218
Chaoul, 84
  therapy, 86
  tube, 84
Charlton, 268
Chemical effect of X-rays, 110
Choke coil, 10, 16
Circuit :
  filament, 68
  Graetz, 92
  Greinacher, 97
  high frequency, 11
  inductive, 7
  noninductive, 7
  primary, 2, 21
  secondary, 2, 21
  Villard, 98
  wattless, 16
Cloud chamber, 153, 261
Cobalt^{60}, 248, 286, 293, 294, 298, 300, 311
Cobalt unit, 294
Cockcroft, 259, 312
Coefficient :
  absorption, 162, 164, 166, 168
  atomic absorption, 168, 169
  electronic absorption, 168
  linear absorption, 162, 163, 164
  mass absorption, 164, 166, 167
Collision :
  disintegration, 243
  ionization by, 48
  scattering, 243
Compton, 151, 155, 157, 168
Condenser :
  meter and dosage, 191
  with electrometer, 189
  with rectifying valves, 95
Conductivity of air, 36, 38, 53
Constant potential, 97
Continuous spectrum, 130, 131
Contrast, meaning of, 141, 142
Contrast sensitivity, 118
Coolidge, 48, 68, 76, 78, 268
Cooling of target, 72
Cork, 296, 297
Corona, 27, 53
Cosmic rays, 283
Cosslett, 145, 147
Coulomb, 43, 183
Counter :
  Geiger-Mueller, 219, 222
  proportional, 222
  scintillation, 224, 225
  4π, 223
Cox, 173
Crookes' dark space, 39
Cross-fire treatment, 201
Cross-section, 169
Curie, 210, 228, 276, 303
Currents :
  alternating, 1, 3
  control of, in X-ray rube, 72, 75
  high frequency, 11
  induced, 2
  ionization, 179, 189
  rectified, 5, 88
  resonating, 13
  saturation ionization, 179
  saturation tube, 75
  sinusoidal, 4
Cycle, meaning of, 4
Cyclotron, 259
  electron, 259, 269
  synchro, 259, 266

Dark space, 39
D.c., 5
Decay :
  coefficient, 232, 241
  of radon, 230, 233
Dees, of cyclotron, 260, 264
Demers, 213, 280, 281, 304
Dempster, 57
Density, photographic, 141
Deposit, active, 237
Depth dosage, 198, 200, 248
Deuterium, 60
Deuteron, 265, 275
  bombardment, 275
Diaphragm :
  and scattered rays, 171
  Potter-Bucky, 172
Diode tube, 67, 88, 90, 100
Disintegration, 237
  collision, 243
  constant, 232, 241
  photo, 278, 280
  scheme, 299, 300
Dosage :
  by condenser-meter, 191
  by ionization, 178
  depth, 198, 200, 248
  gamma radiation, 186
  k factor, 298
  n unit, 282
  neutron, 282
  of X-rays, 177, 178
  pastilles, 178
  roentgen unit, 182, 186
Dose :
  air, 195
  back scatter, 195
  integral, 205
  permissible, 314
  rate, 178
  tissue, 195
Dose-rate meter, 195
Dosimeter, 193, 195
Duane, 128, 139
Dushman, 89
Dynode, 224

Effective :
  absorption coefficient, 164
  half-life, 297
  wave length, 137
Einstein, 287, 288
Einstein's law, 287, 303
Electromagnetic :
  induction, 2
  waves, 105, 106
Electromagnetism, 1
Electrometer, 189, 191
Electromotive force (e.m.f.), 2
  of inductance, 7
Electron :
  bombardment, 48
  capture, 219
  equilibrium, 184, 188, 194
  gun, 46
  pair, 290
  synchrotron, 259, 269
Electronic :
  absorption coefficient, 168
  equilibrium, 184, 188, 194
Electrons, 45
  Auger, 218
  internal conversion, 218
  photo, 111, 119, 152, 154, 157
  recoil, 154, 157
  secondary, 184, 185, 218
  thermionic emission of, 45, 66
Electron-volt, 45
Electroscope, 36, 110
  alpha ray, 214
  beta ray, 215
  gamma ray, 218
Electrostatic :
  generator, 251
  voltmeter, 29
Emanation, radium, 227, 229
Energy :
  and destruction of matter, 303
  and mass, 287, 303
  by calorimeter, 203
  flux and the roentgen, 205
  radiation of, 177
Equilibrium :
  amount of isotope, 310
  electronic, 184, 188
  radon and radium, 235
  secular, 242
  transient, 242
Evans, 220
Exponential law, 110, 163
Extrapolation chamber, 196

Failla, 197, 232
Farad, 11
Faraday, 2
Fermi, 279
Filament circuit, 68

Film badge, 316
Filters, 113
Filtration and wave length, 157, 159
Fission of nuclei, 278, 303
Fission products, 297, 312
Fluorescence :
  and cathode rays, 40
  and radium, 210
  and X-rays, 108
Fluorescent :
  screen, 109
  X-rays, 150, 152
Fluorography, 109
Flux :
  energy, and the roentgen, 205
  magnetic, 1
Focal spot, 71, 145
Focusing X-ray tube, 73
Focus, line, 79
Free air chamber, 191
Frequency, a.c., 5
Frisch, 304
Full-wave rectification, 92, 94

Gamma, photographic, 142
Gamma rays, 186, 211, 216
  dosage, 186
  in nuclear reactions, 278, 280, 289
Gauss, 1
Geiger, 220
Geiger-Mueller counter, 219, 222
Generating voltmeter, 255
Generator :
  cascade, 250
  electrostatic, 251
  Van de Graaff, 251
Geometric unsharpness, 143
Gold^{198}, 286, 293, 300
Goldhaber, 289
Goldstein, 54, 55
Goltze, 79
Graetz circuit, 92
Grain size, 144
Gram-rad, 205
Gram-roentgen, 205
Gray, 151
Greinacher circuit, 97
Grenz :
  rays, 84, 113, 194
  tube, 84
Grid :
  action tube, 72
  bias, 101
  Lysholm, 173
  of valve, 100
  ratio, 173
  stationary, 173
  therapy, 202

Hahn, 303
Half-life, 232
  effective, 297
Half-period, radon, 232
Half-value-layer (h.v.l.), 113, 115
Half-wave rectification, 89, 92
Hall, 185
Halmshaw, 144
Hard :
  tube, 39
  X-rays, 112
Harkins, 276
Harmsen, 56
Harris, 297
Hartley circuit, 104
Heavy water, 60, 64, 307
Henderson, 264
Henry, 2
  unit, 8
Hevesy, 291, 292
High frequency current, 10
Hills, 173
Homogeneous X-rays, 110, 127
Hönigschmid, 240
Hurst, 282
H.v.l., 113, 115
Hysteresis, 23

Image intensifier, 109, 118, 121
Impedance, 9
Implantation, 227
Indicators, radioactive, 291
Inductance, 7
Induction, electromagnetic, 2
Inductive :
  circuit, 7, 8
  reactance, 9
Infra-red, 106
Inherent regulation, 24
Inherent unsharpness, 143
Insulation, transformer, 23
Integral dose, 205
Intensifier, image, 109, 118, 121
Intensifying screen, 109
Intensity :
  absolute, 177
  and voltage, 130
  inverse square law, 177
  of magnetic field, 1
  of X-rays, 130, 177

Internal conversion electrons, 218
Inverse voltage, 89
Iodine^{131}, 286, 293, 298, 300
Ionization, 36, 47
  and dosage, 178
  by collision, 48
  chamber, 180, 181, 190, 191, 194, 316
  conversion process, 185
  current, 179
  effect of X-rays, 110
  saturation current, 179
  specific, 212, 315
Ionizing agent, 36
Ions, 37
  recombination of, 181
  seeing, 153
Ireland, 295
Isobars, 59
Isodose curves, 202
Isotopes, 55, 61, 238, 286, 297, 306
  in diagnosis, 294
  in therapy, 293
  medical uses, 291, 297
  separation of, 61, 62
  table of, 286, 319
  uranium, 62, 306

Johns, 248
Joliot, 276, 284, 290
Jolles, 202
Jordan, 184

Kemp, 185
Kenotron, 89
Kerst, 266, 268, 269
K factor, 132, 134
Korff, 223
K wave lengths, 132, 134
  critical absorption, 161

Lamerton, 297
Laue (von), 125
Laughlin, 203, 269
Laurence, 216
Lauritsen, 184
Lawrence, 262, 263, 265
Lea, 166
Lenard, 48
Lenz's law, 7
Lindemann glass, 110
Linear absorption coefficient, 162, 163, 164
Linear accelerator, 259, 270, 278
Linkages, magnetic, 2, 7
Lithium window, 110
Luminophor, 225
Lysholm, 173
  grid, 173
L wave lengths, 132, 134

Machlett tube, 85, 110
Magnetic :
  deflection, 40
  field, 1
  flux, 1
  induction, 1
  linkages, 2, 7
Mass :
  absorption coefficient, 164, 166, 167
  and energy, 287, 303
  conservation of, 273, 288
  number, 61
  of neutron, 289
  spectrograph, 58, 62, 273
  spectrum, 58
Mayneord, 152, 194, 205, 207, 226, 227, 269, 295
Medium X-rays, 112
Meitner, 304
Menzel, 60
Mesh chamber, 194
Mesothorium, 245
Metalix X-ray tube, 77
Meter, dose-rate, 195
Microradiography, 145
Microscope, X-ray, 145
  magnification of, 147
Millikan, 43
  oil-drop experiment, 43
Mitchell, 202
Moderator, 307
Monochromatic X-rays, 110
Motor principle, 260
Murphy, 60
M wave lengths, 132, 134

Nemet, 173
Neutron :
  bombardment, 279
  capture, 279
  detection of, 280
  discovery of, 276
  dosage, 282
  energy classification, 278
  from fission, 278, 305
  mass of, 289
  permissible levels, 315
  production of, 278
  therapy, 281
  unit, 282

Nier, 62
Nixon, 145, 147
Noninductive circuit, 7, 8
Nuclear bombardment, 273
Nuclear reactor, 307
Nucleus of atom, 46, 242
  fission of, 278, 303
Nuclide, 59
N unit, 282

Oersted, 1
Oil-immersion tube, 83
Oosterkamp, 195
Oscillator, triode, 104
Oscilloscope, 49

Pair production, 156, 291
Paneth, 279, 291, 292
Pastille, 178
Peak voltage, 6
Penetrating effect of X-rays, 111
Penetration and wave length, 132
Permissible dose, 314, 315
Phantom, 196, 199
Phase, meaning of, 14
Phosphors, 109
Phosphorus^{32}, 285, 292, 293, 296, 300
Photocathode, 122, 224
Photodisintegration, 278, 280
Photoelectric :
  cell, 120
  effect, 111
  timer, 123
Photoelectrons, 111, 119, 152, 154, 157
Photographic density, 141
Photographic effect of X-rays, 108
Photomultiplier, 224
Photovoltaic cell, 120
Photronic cell, 120
Pile, atomic, 307
Planck's constant, 135
Polonium, 210
Porous barrier, 63
Ports of entry, 201
Positive rays, 54
Positron, 283, 285, 291
Potter-Bucky diaphragm, 172
Power, a.c., 16
Power factor, 16
Power rating, 23
Primary :
  beta rays, 218
  circuit, 2, 21
  voltmeter, 28
  X-rays, 150, 152
Proportional counter, 222
Protection, 77, 313
  barriers, 316
  film badge, 316
  monitoring, 316
  permissible dose, 314
  pocket chamber, 316
Proton, 60, 243, 266
  bombardment, 274
  synchrotron, 259, 270

Quality :
  and film badge, 317
  and h.v.l., 113, 133
  and voltage, 112
  of X-rays, 112, 177
Quantum, 135
Quastler, 269
Quimby, 138, 197, 198, 199, 202, 218, 231, 292

Rad, 203
Radiation :
  of energy, 177
  quantity of, 177
Radiations from radium, 211
Radioactive :
  families, 239, 244
  indicators, 291
  tracers, 291
Radioactivity :
  artificial, 283, 284
  average life, 234
  discovery of, 210
  disintegration constant, 232
  from reactors, 312
  natural, 210
  transformation constant, 232, 241
  transmutation, 237
Radioelements, 285
  Cobalt^{60}, 248, 286, 293, 294, 298, 300, 311
  Gold^{198}, 286, 293, 300
  Iodine^{131}, 286, 293, 298, 300
  Phosphorus^{32}, 285, 286, 292, 293, 296, 300
  Sodium^{24}, 285, 286, 292, 300
  Strontium^{90}, 286, 293
  Tantalum^{182}, 286, 293
  Thulium^{170}, 286, 295, 299
  Xenon^{133}, 295
Radiography, 141
  and scattering, 170

contrast, 141
density, 141
focal spot, 71, 145
micro, 145
multisection, 148
resolution, 144
unsharpness, 143
Radium, 210
beam therapy, 227
dosage, 229
emanation, 227
family, 239
half-period, 239
in treatment, 227
needle, 227, 293
radiations from, 211
seeds, 227, 293
strength of source, 228
Radon, 227, 229
decay of, 230, 233
growth of, 234
half-period, 232
Ramsay, 237
Rating :
of transformer, 23, 25
of X-ray tube, 81, 93
Rays :
alpha, 211
beta, 214
canal, 54
cathode, 36
cosmic, 283
gamma, 186, 211, 216
Grenz, 84
positive, 54
roentgen (see X-rays)
R.b.e., 314
Reactance :
inductive, 9
capacitive, 11
Reactor, atomic, 307, 309
and radiology, 310
Read, 257
Recoil electrons, 154, 157
Recombination of ions, 181
Rectification, 5, 88
and tube rating, 93
full-wave, 92, 94
half-wave, 89, 92
self, 88
Rectifier :
hot filament, 67
valve, 89
Rectifying valve, 88, 91
Regulation, inherent, 24
Reimes, 226
Rem, 315
Rep, 205
Resolution, 144
Resonance :
parallel, 13
series, 13
R.m.s., 6
Roentgen, 108
and energy flux, 205
and the rad, 203
gamma ray unit, 186
rays (see X-rays)
tubes, 66, 68
X-ray unit, 182, 186
Rogers, 110
Rose, 232
Rotational therapy, 201
Royds, 237
Rutherford, 220, 237, 244, 273, 276

Safford, 255
Saturation :
ionization current, 179
tube current, 75
Savitch, 303
Scanning, 295
Scatter, back, 195
Scattered X-rays, 150, 152, 170, 196, 199
and radiography, 170
and recoil electrons, 154
Scattering :
absorption coefficient, 166
and diaphragms, 171
back, 195
collisions, 243
of alpha rays, 212
Schall, 103
Scintillation counter, 224, 225
Scintillations, 213, 243
Screen, fluorescent, 109
Secondary :
beta rays, 217, 218
circuit, 2, 21
electrons, 184, 185, 218
X-rays, 150
Seeman, 173
Seeman spectrograph, 30, 128
Self-inductance, 8
Self-rectification, 88
Shockproof tube, 82
Sieve therapy, 202

Sievert unit, 229
Sinusoidal :
  current, 4
  curve, 14
Smith, 292
Smithers, 249
Soddy, 58, 237
Soft :
  tube, 39
  X-rays, 112
Somervil, 194
Space charge, 75
Spark-gap meter, 25, 251, 255
Spark length and voltage, 26, 251, 255
Specific activity, 297, 311
Specific ionization, 212, 315
Spectrograph :
  mass, 58, 62, 273
  Seeman, 30, 128
  X-ray, 128
Spectrometer :
  mass, 62
  X-ray, 127
Spectrum :
  continuous, 130, 131
  infra-red, 106
  line, 130, 131
  mass, 58
  ultra-violet, 106
Spiegler, 316, 317
Spiers, 194, 205
Spinthariscope, 213
Splettstosser, 173
Stabilizer, voltage, 32, 77
Standard chamber, 181, 187
Statcoulomb, 43, 183
Statvolt, 45
Stephenson, 317
Step-down transformer, 22
Step-up transformer, 22
Stoddard, 114
Stopping power, 214
Stout, 296, 297
Strassmann, 303
Strontium^{90}, 286, 293
Supervoltage, 248
  measurement of, 255
  tubes, 255
Sweep circuit, 50
Synchro-cyclotron, 266
Synchroton :
  electron, 49, 269
  proton, 259, 270
Tantalum^{182}, 286, 293
Target :
  cooling of, 72
  of X-ray tube, 49, 51, 71
  water-cooled, 72
Taylor, 113, 191
Tele-autograph, 295
Telecurie therapy, 227
Teletherapy, 293
Therapy :
  beta ray, 293
  Chaoul, 84
  gamma ray, 228
  grid, 202
  isotopic, 293
  neutron, 281
  radium beam, 227
  rotational, 201
  sieve, 202
  telecurie, 227, 293
  X-ray, 177
Theratron, 294
Thermal reactor, 309
Thermionic emission, 45, 66
Thimble chamber, 181, 190
Thomson, 55, 56
Thorium, 245
Thulium, 295, 299
Thyratron, 123
Timer :
  photoelectric, 123
  triode, 102
Tissue dose, 195
Tomography, 147
Tracers, radioactive, 291
Transformation constant, 232, 241
Transformations, radioactive, 237
Transformer, 21
  efficiency of, 23
  insulation, 23
  losses, 23
  power rating, 23, 25
  primary, 21
  secondary, 21
  step-down, 22
  step-up, 22
Transient equilibrium, 242
Transmutation, 237, 242
Treatment :
  cross-fire, 201
  neutron, 281
  radium, 227
  X-ray, 177

Triode valve, 100
as amplifier, 102
as detector, 102
as oscillator, 104
as timer, 102
Tritium, 60
Trout, 194
Trump, 253, 254, 255, 258
Tube :
Chaoul, 84
Coolidge, 68
current, control of, 72, 75
gas X-ray, 66
Grenz, 84
grid action, 72, 130
hot filament, 68, 70
low voltage, 84, 85
Machlett, 85, 110
massive anode, 72
metalix, 77
multisection, 256
oil-immersion, 83
photomultiplier, 224
preparation of, 70
protection, 78
radiator, 72
rating, 81, 93
Roentgen, 66
rotating anode, 79, 80
saturation current, 74
self-rectifying, 88
shockproof, 82
supervoltage, 256
water-cooled, 72
window, beryllium, 85
vacuum, 39, 67, 88, 100
X-ray, 66, 68
Turner, 317

Ultra-violet, 106
Unsharpness :
geometric, 143
inherent, 143
Uranium, 62, 210
isotopes, 62, 244, 306
fission, 306
Urey, 60

Vacuum tube, 39, 67, 88, 100
Valve :
amplification factor, 102
characteristic curves, 90, 101
diode, 67, 88, 100
rectifier, 89
rectifying, 88
triode, 100, 102, 104
types of, 91
with condensers, 95
Van de Graaff, 251, 253, 254, 255, 258
generator, 202, 251
Van der Tuuk, 115
Veale, 223
Vennart, 110
Victoreen, 194
condenser-meter, 191
Villard circuit, 98
Visual acuity, 119
Voltage :
and intensity, 130
and quality, 112
and shortest wave length, 129, 248
and spark length, 26
control of, 30, 31
high, 21, 25, 248
inverse, 89
measurement of, 29, 255
peak, 6
stabliizer, 32, 33, 77
super, 248
Voltmeter :
electrostatic, 29
generating, 255
primary, 28

Walton, 259
Water, heavy, 60, 64, 307
Watson, 148
Wave length :
and atomic number, 132
and ionization chambers, 191
and penetration, 132
corresponding, 132, 136
critical absorption, 157, 160
effective, 137
K, *L* amd *M*, 132, 134
measurement of, 125
shortest, 129, 248
Waves, electromagnetic, 105, 106
White radiation, 130
Whitehead, 312
Wien, 54
Wilsey, 171
Wilson, 153

Xenon^{133}, 295
X-ray microscope, 145
X-rays :
absorption of, 114, 118

bremsstrahlung, 130
characteristic, 129, 131, 150, 218
discovery of, 108
dosage, 177, 178
fluorescent, 150, 152
general, 129
generation of, 49
Grenz, 84, 113, 194
hard, 112
homogeneous, 110, 127
independent, 130
intensity of, 130, 177
medium, 112
modified, 151
monochromatic, 110
origin of, 49
primary, 150, 152
properties of, 108, 110
protection, 77, 313
quality of, 112, 115, 177
reflection of, 126
scattered, 150, 152, 170, 196, 199
secondary, 150
spectrum, 130, 131
soft, 112
superhard, 113
unmodified, 151
wave lengths, 125
white, 130
X unit, 105

Ytterbium, 299, 300

PRINTED IN GREAT BRITAIN BY
ROBERT MACLEHOSE AND CO. LTD
THE UNIVERSITY PRESS, GLASGOW

Date Due

MAR 2 3 1962

UNIVERSITY OF MICHIGAN
3 9015 00133 7354